Fe line diagnostic in accreting black holes

Accretion under strong field gravity regime

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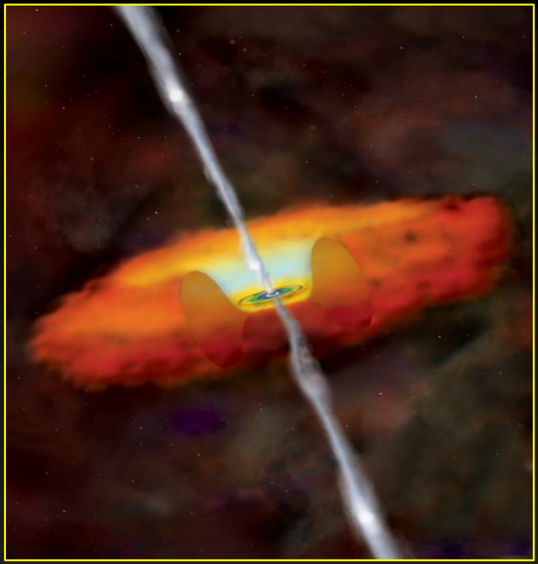
eXTP Workshop - Rome 2017

The two flavours Accreting BH

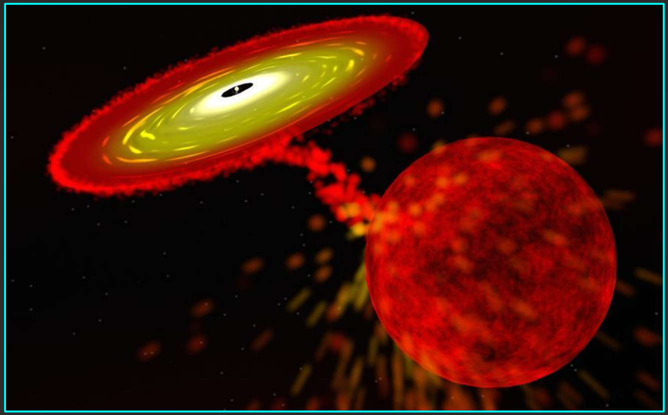
stellar mass BHs scattered in galaxies
(X-ray binaries)
supermassive BHs in the center of
galaxies (AGN and quasars)



10^6-10^9 M_{sun}
R_g/c=50s

Close to the BH, most of the physical processes are the same. we can learn a great deal by comparing the two families

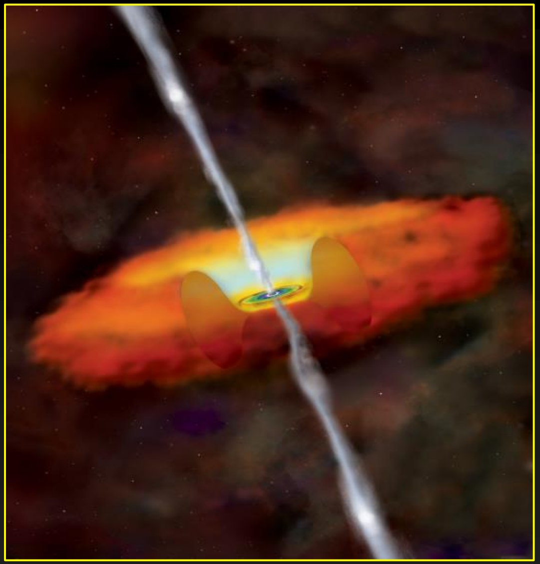
8-10 M_{sun}
R_g/c=50μs



What really matters in these studies is the n. of photons (i.e. flux, F_{obs}) per unit of light crossing time scale
$\sim R_g/c \sim GM/c^3 \sim 500\ M_8$ s

(some) Open questions

- ✓ how does matter behave in the strong GR field regime?
- ✓ what are the processes near the event horizon? (accretion/ejection)
- ✓ How does the spin affect the emission/jet processes?
- ✓ how are BH spins distributed? (BH birth/growth)
- ✓ . . . .

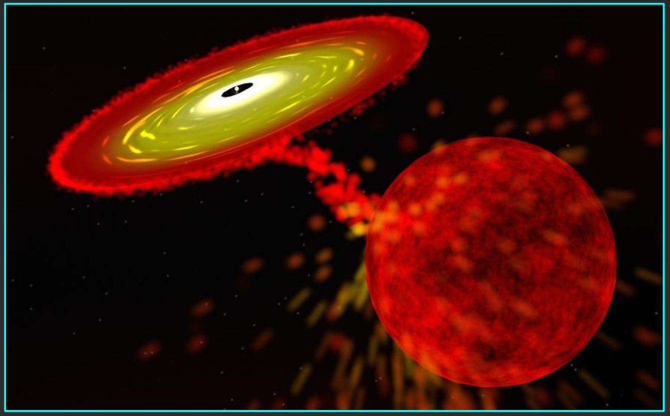


10^6-10^9 Msun
R/c=50s

X-ray tools (some)

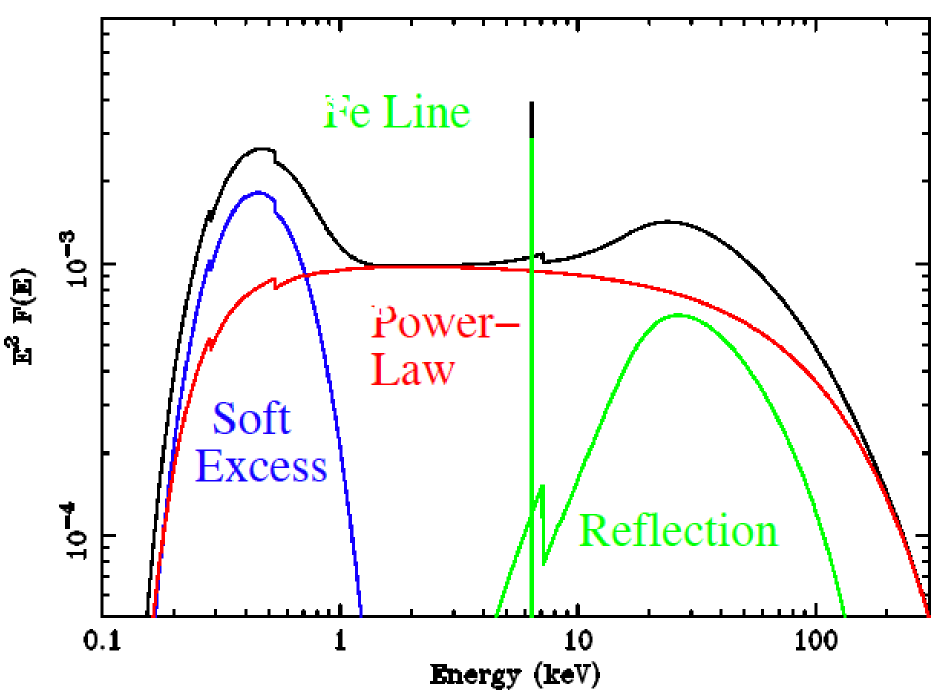
Relativistic reflection - spectral
Thermal disc emission - spectral
High Frequency QPOs - timing
Polarization degree - polarimetry

8-10 Msun
R/c=50μs

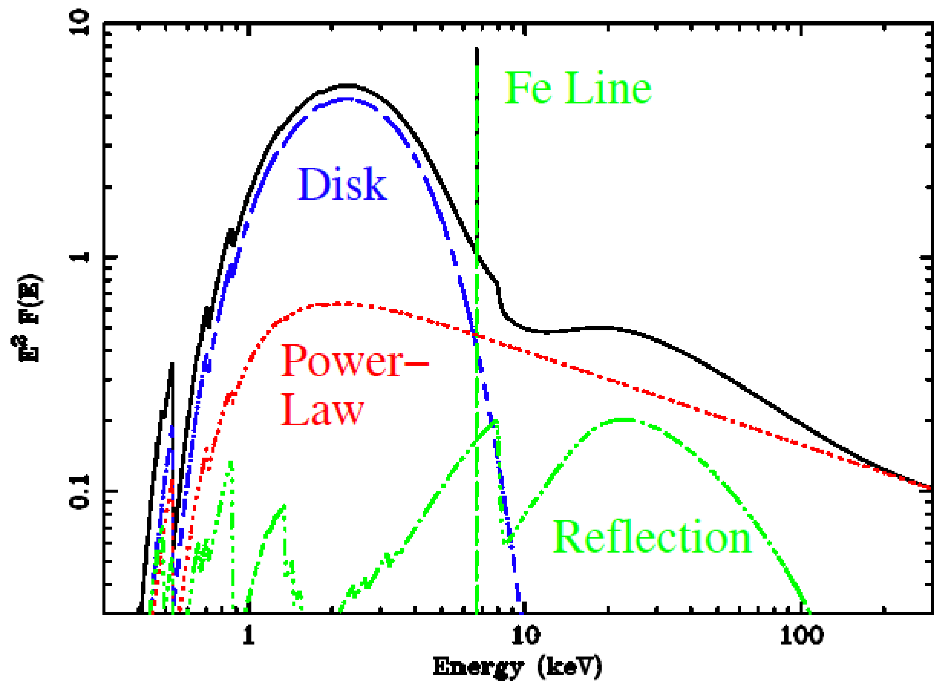


The Broadband X-ray spectra

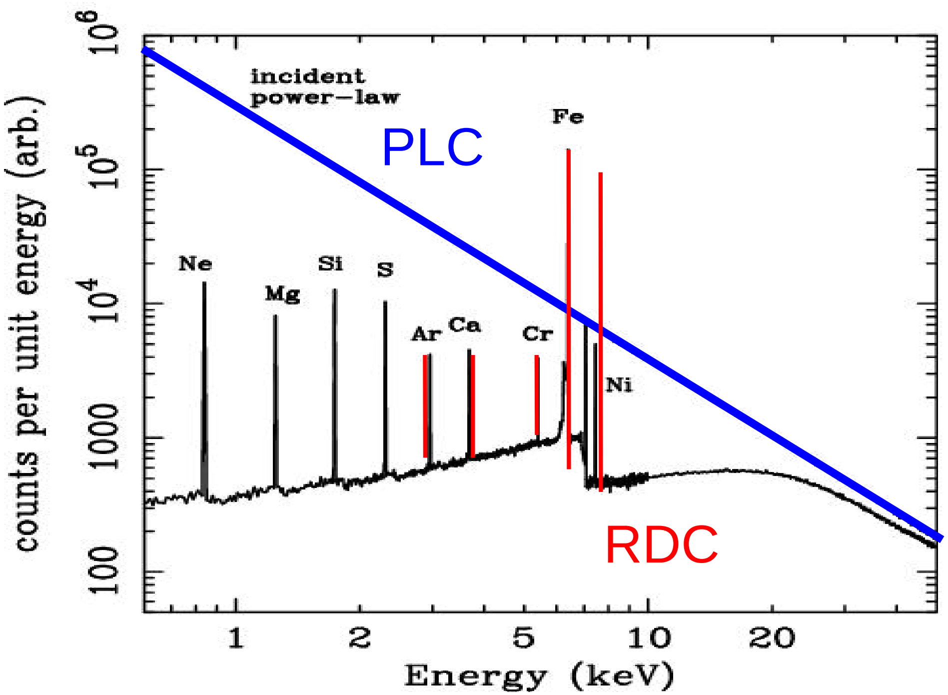
Type 1 AGN

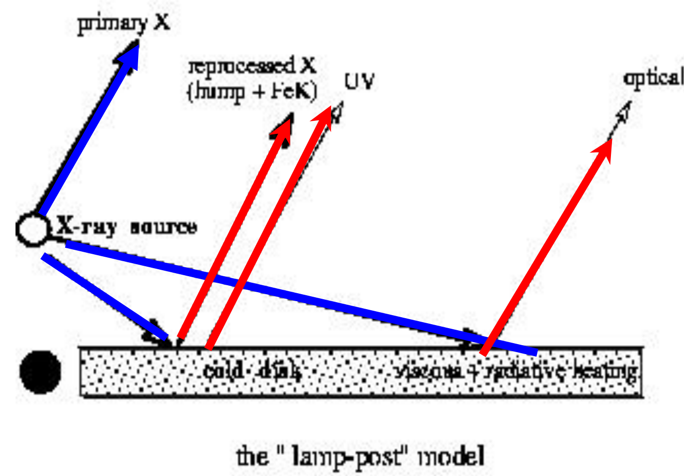


XRB-high soft state



The X-ray reflection spectrum





Compton Scattering &
Photoelectric absorption

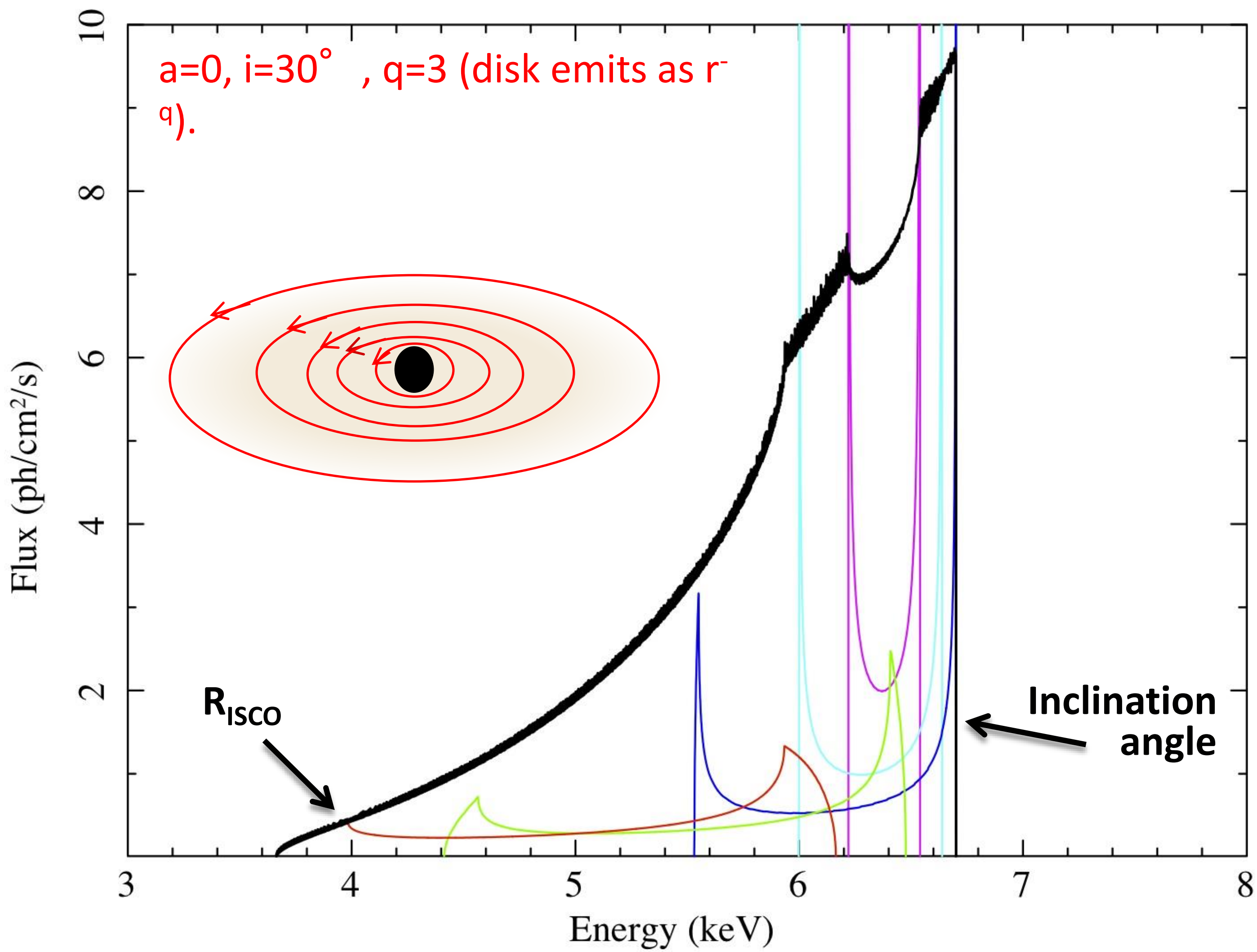
∝ Inclination

∝ Ω/2Π (coverage, isotropy)

 Ab

Reynolds 96
Ross & Fabian 99, 05

Fe Kα emission line from different disk radii



The big advantage of this method: it is independent on the BH's mass. Everything is expressed in terms of R_g

Brenneman & Reynolds 2006; Dauser+ 2010

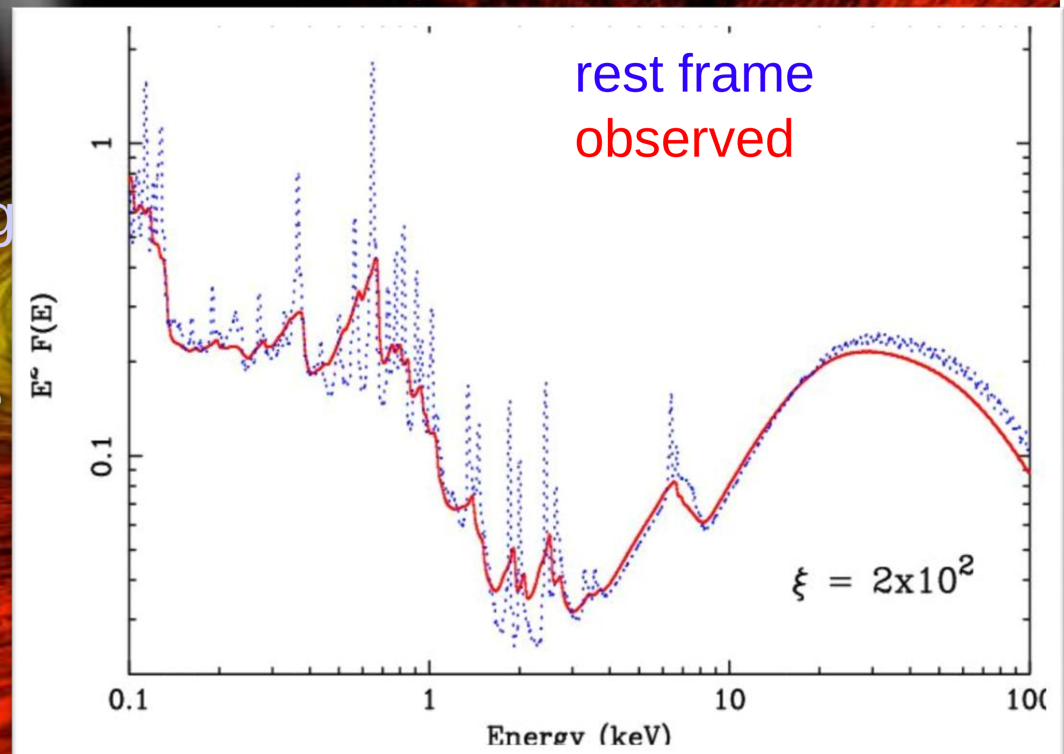
X-ray broad band reflection: relativistic effects

Doppler shifts

relativistic beaming

gravitational redshift

gravitational light bending



The Effects of SFG are all involved in modelling the spectral-timing results in a wide energy band

SFG BH diagnostic: Fe line (variability)

- SMBHs - AGN
  - ✓ Disk Fe line profile
  - ✓ Phase resolved Fe line. Orbiting Hot Spot
  - ✓ X-ray reverberation. Time lags
- Stellar mass BH - XRB
  - ✓ Disk Fe line profile
  - ✓ Continuum fitting
  - ✓ X-ray reverberation. Time lags
  - ✓ QPOs
  - ✓ QPOs phase resolved polarimetry

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  - ✓ X-ray reverberation. Time lags - *Uttley's talk*
- Stellar mass BH - XRB
  - ✓ **Disk Fe line profile**
  - ✓ **Continuum fitting -** *Lijun's talk*
  - ✓ X-ray reverberation. Time lags
  - ✓ QPOs - *Stevens's talk*
  - ✓ QPOs phase resolved polarimetry - *Ingram's talk*


AGN SMBHs

Measuring the SMBHs spin

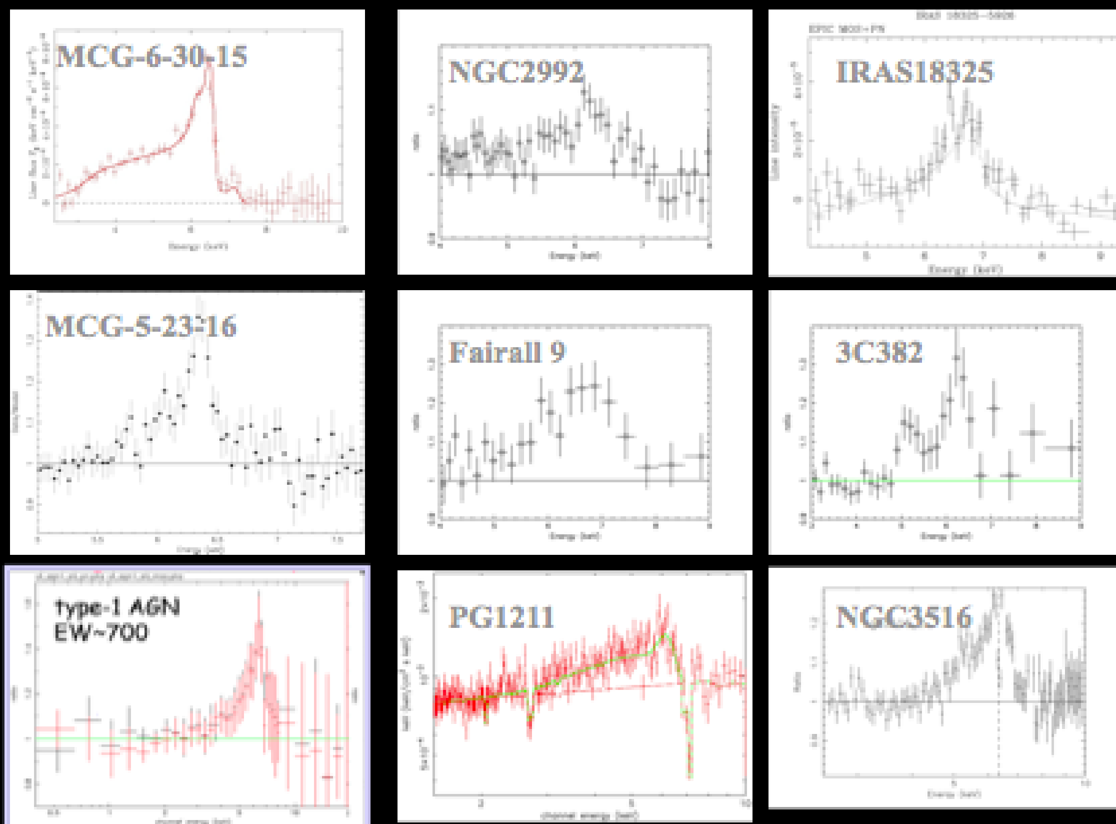
Ingredients

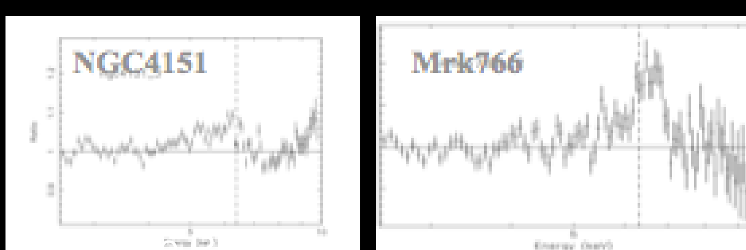
- High S/N in X-ray band: $\geq 2\mathrm{x}10^5$ counts in 2-10 keV
- Broad line with $r_{in} \leq 10\ r_g$ in unobscured (N_H<10^{22} cm^{-2}) AGN
- Broad energy band is needed to model simultaneously all spectral complexities: Complex absorption, disk ionization, disk emissivity, soft excess, Fe abundance

~30 bright AGN in the nearby Universe (Miller+ 2007, Nandra+ 2007, de La Calle Perez+ 2010, Reynolds 2013, Marinucci+14, Patrick+14, Risaliti+13) but ~10^{12} accessible universe

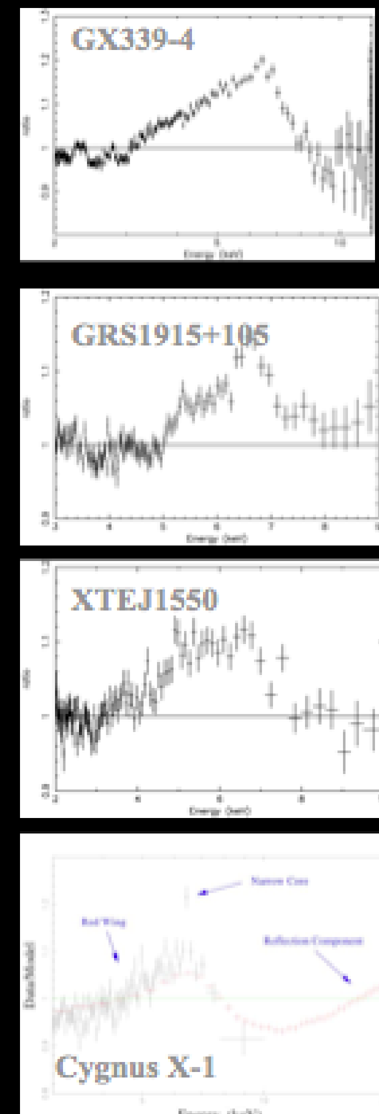
Very Broad Fe-K line profiles with XMM in:

AGN



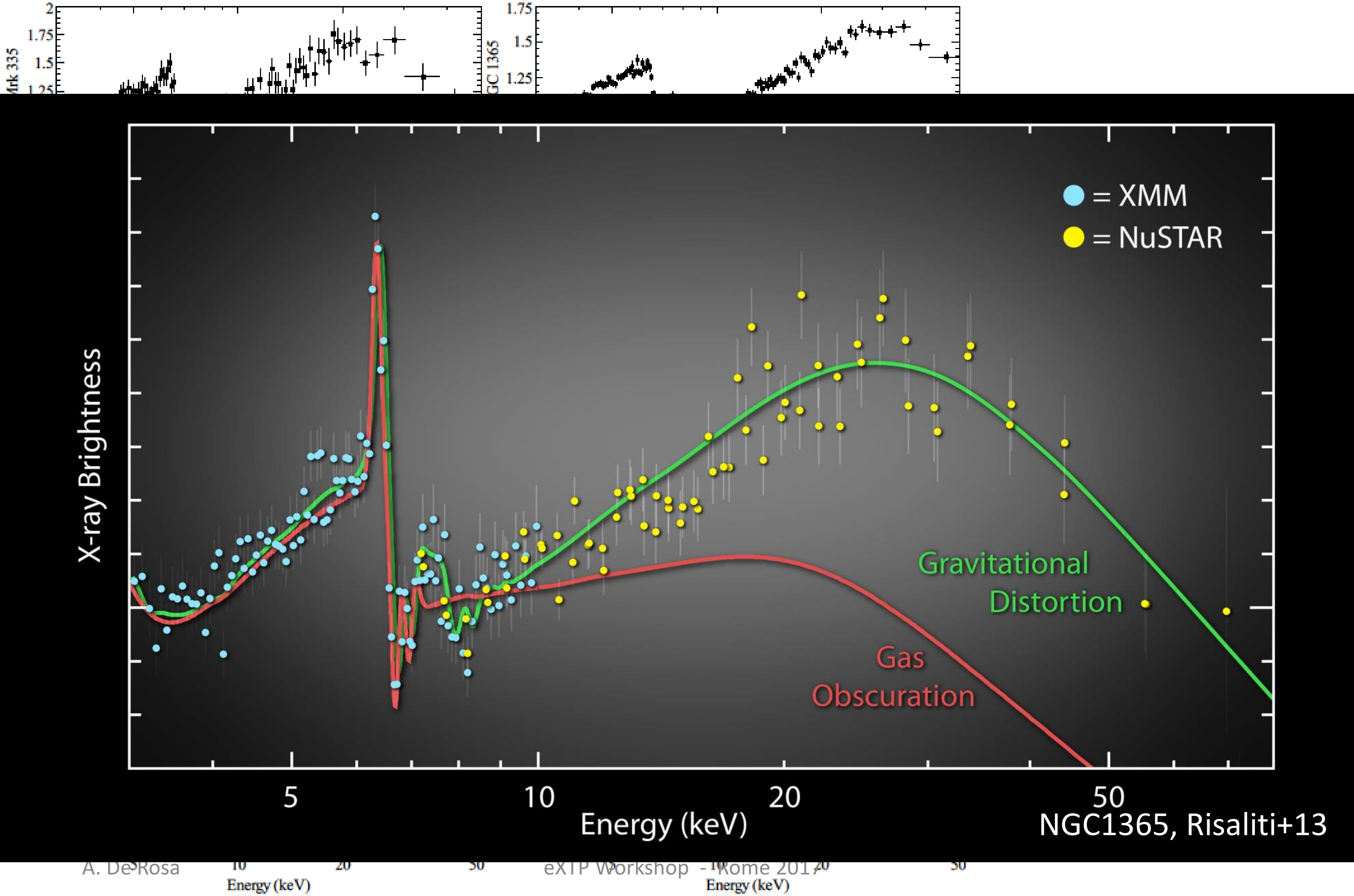


X-ray Binaries



Similar line profiles from stellar-mass and super-massive black hole systems… demonstrates insensitivity of line profile to mass

Broadband relativistic reflection with NuStar

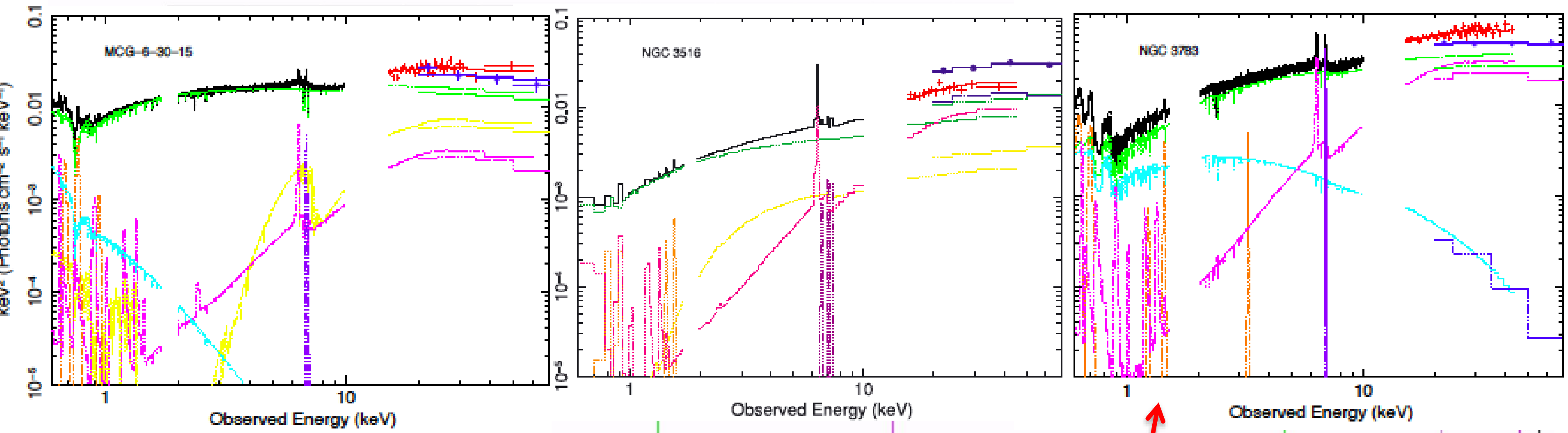


NuStar BH AGN spin

Target	Spin	Data	Reference
1H0707-495	> 0.988	XMM-Newton/NuSTAR	Kara et al. (2015)
Ark 120	~ 0.5	XMM-Newton/NuSTAR	Matt et al., 2014
Fairall 9	0.973 ± 0.003	XMM-Newton/NuSTAR	Lohfink et al. (2016)
MCG-6-30-15	$0.91^{+0.06}_{-0.07}$	XMM-Newton/NuSTAR	Marinucci et al., 2014a
Mrk 335	> 0.9	Swift/NuSTAR	Parker et al., 2014
NGC 1365	> 0.97	XMM-Newton/NuSTAR	Risaliti et al., 2013 Walton et al., 2014
NGC4151	> 0.9	Suzaku/NuSTAR	Keck et al. (2015)
SWIFT J2127.4	$0.58^{+0.11}_{-0.17}$	XMM-Newton/NuSTAR	Marinucci et al., 2014b

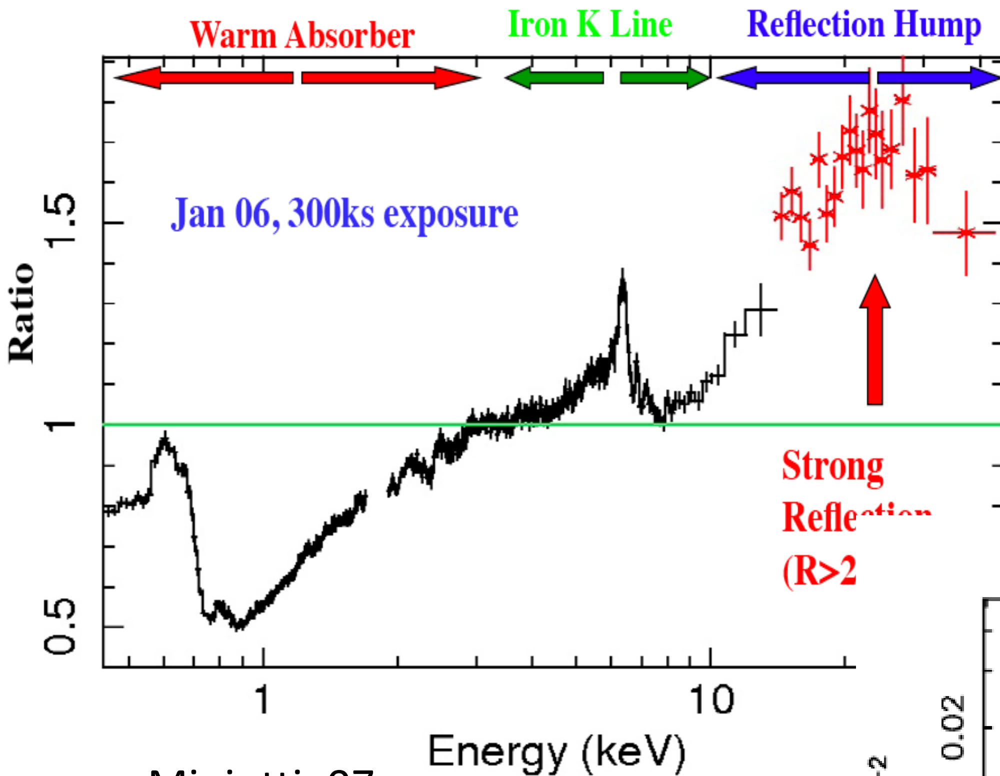
Credit A. Marinucci

Measuring black hole spins in AGN: where do we stand?



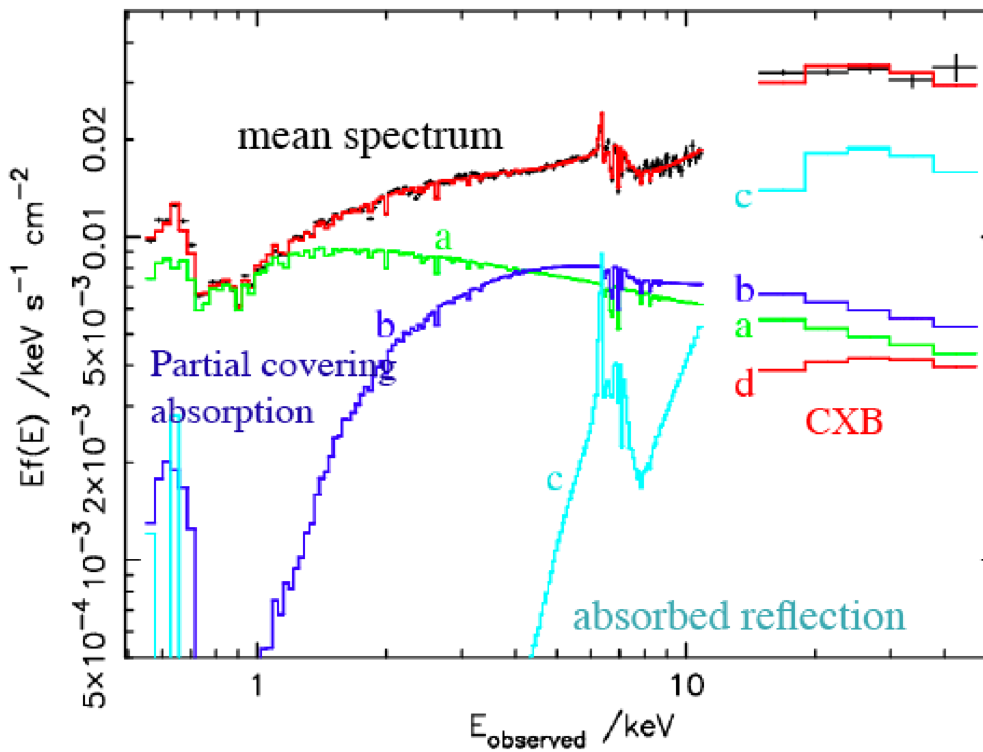
The current uncertainties on the continuum decrease the statistical quality of present measurements (if the continuum is properly modelled) and, more importantly, may introduce systematic errors on spin (if the continuum is improperly modelled).

Relativistic vs absorption scenario



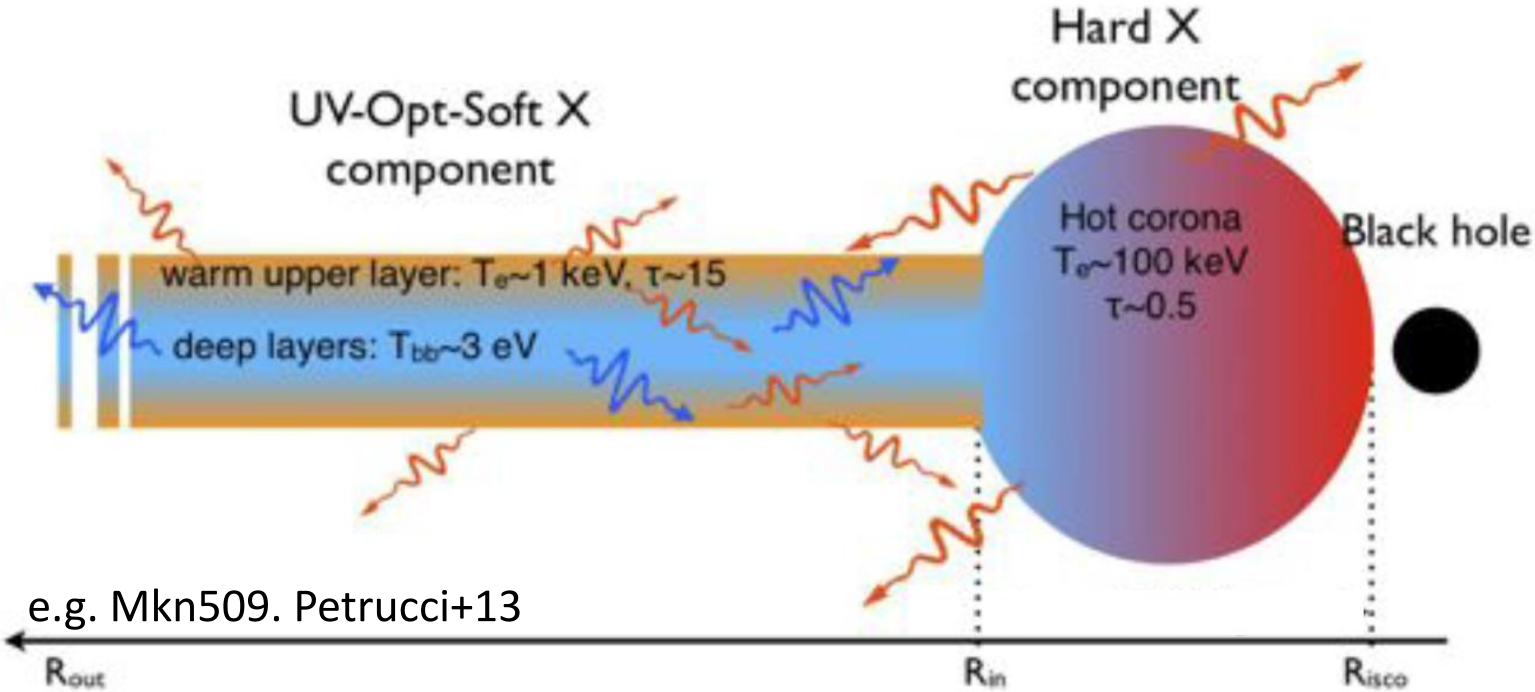
Miniutti+07

Miller+08



Physically consistent broadband reflection model

Soft-excess NGC 3783



e.g. Mkn509. Petrucci+13

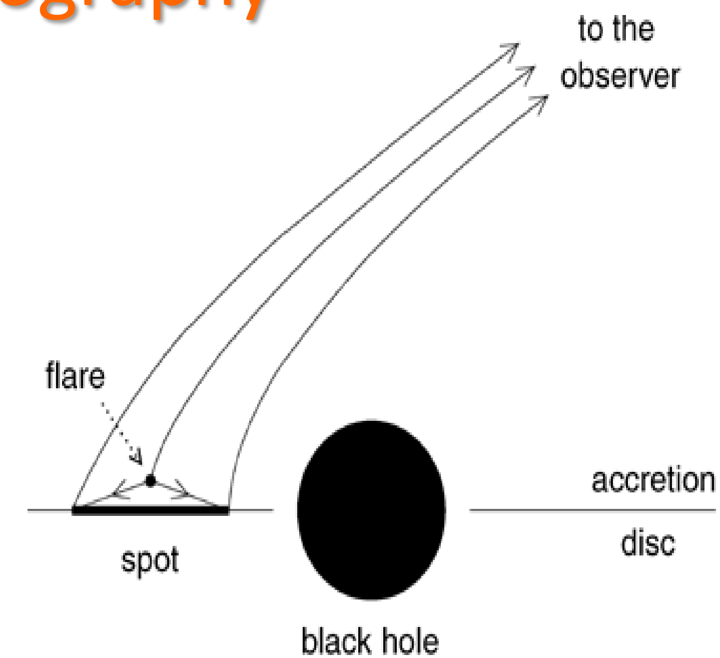
Soft excess <2 keV reproduced with Scattered component + relativistic reflection

a>0.9 Brenneman+11

Soft excess <2 keV reproduced with comptonized component a<0.3 Patrick+11

Key measurement: Time resolved spectral variability disk Doppler tomography

AGN variability is likely associated to “activation” of the X-ray regions above the disk. The flares produce an echo in the observed reflection components on time-scales comparable light-crossing of 1 R_g



While *time averaged* Fe profiles can be expressed in terms of r_g, losing any information about BH mass, assuming the ‘hotspot’ (keplerian) corotating with the disc, the orbital period (and then the BH mass) can be measured

$$T_{orb}=310\ (r^{3/2}+a)M_7\ \mathrm{s},$$

Iwasawa+04
De Marco+08

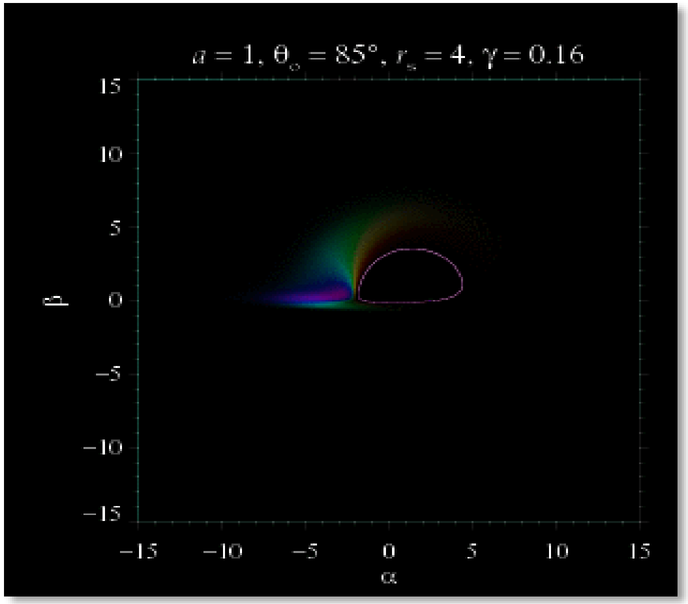
Orbiting spots: Disc Doppler tomography

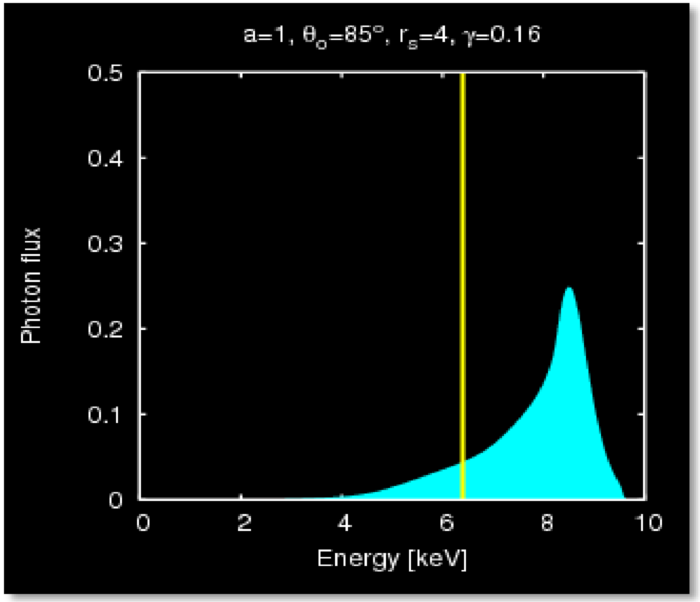
reflection components vary on orbital period time-scales

T_{orb}=310 $(r^{3/2}+a)M_7$ s

From **time resolved spectroscopy** it is possible to derive the radius both in units of the BH mass and in standard units

→ BH mass (and l.l to the spin)

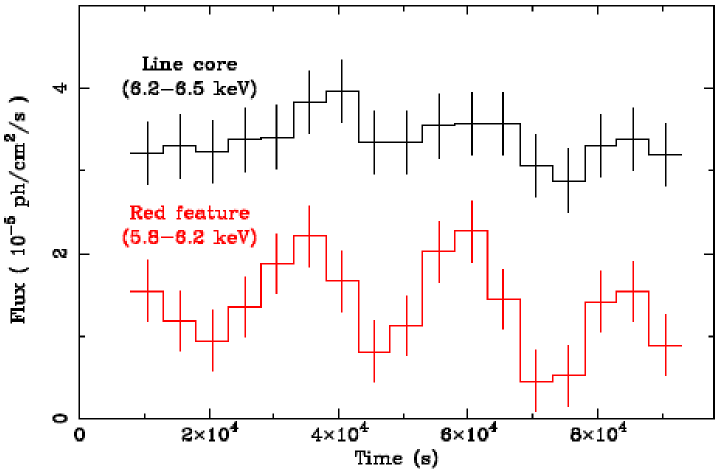




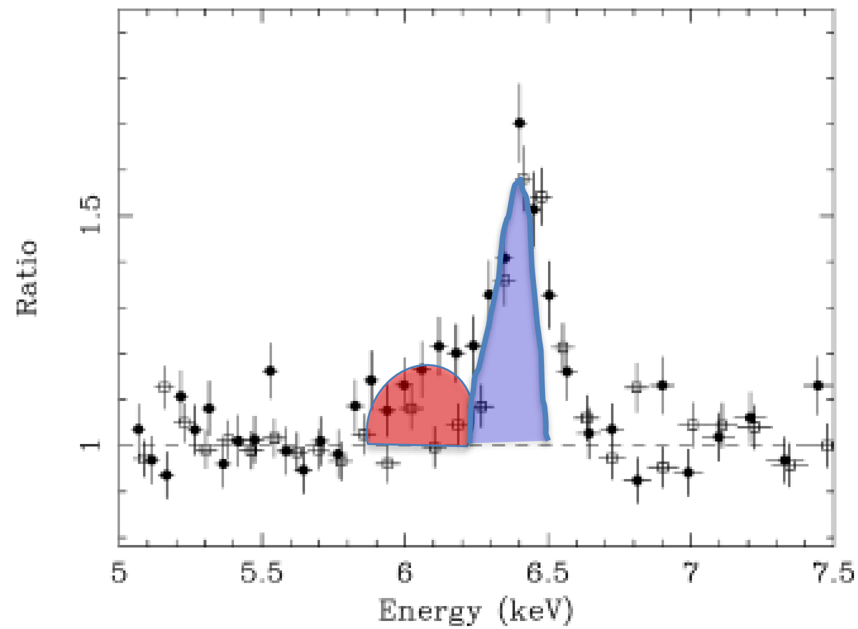
Credit
M. Dovciak

Orbiting spot observations: NGC3516

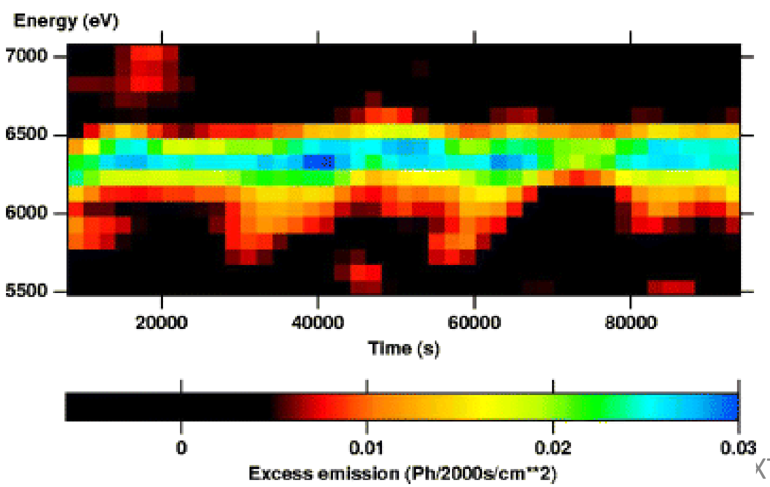
Time averaged line(s) XMM profile 5ks bin



The Fe K line profiles during the on (solid circles) and off (open squares) phases of the red feature.

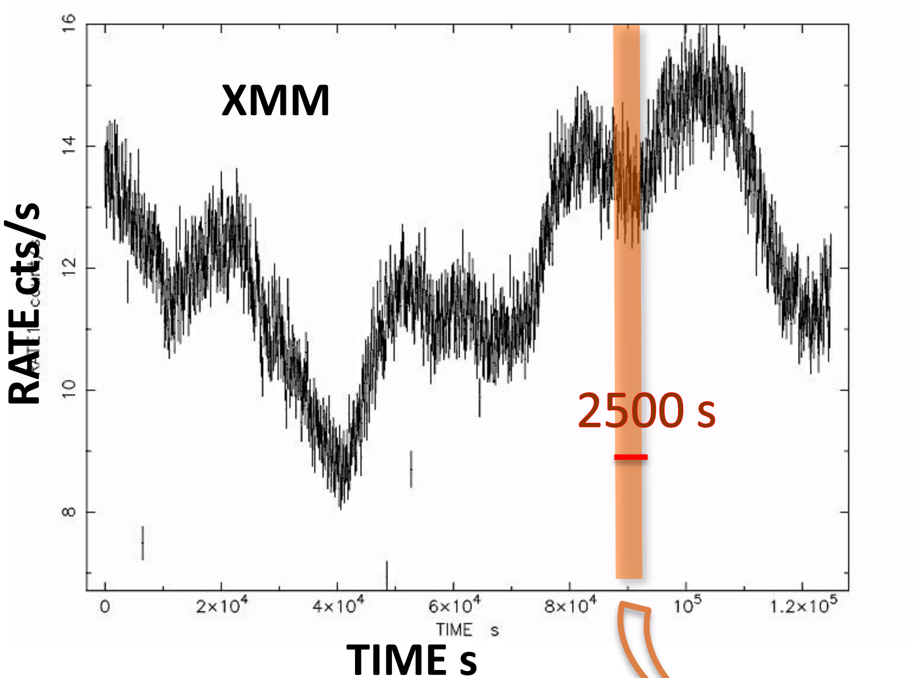


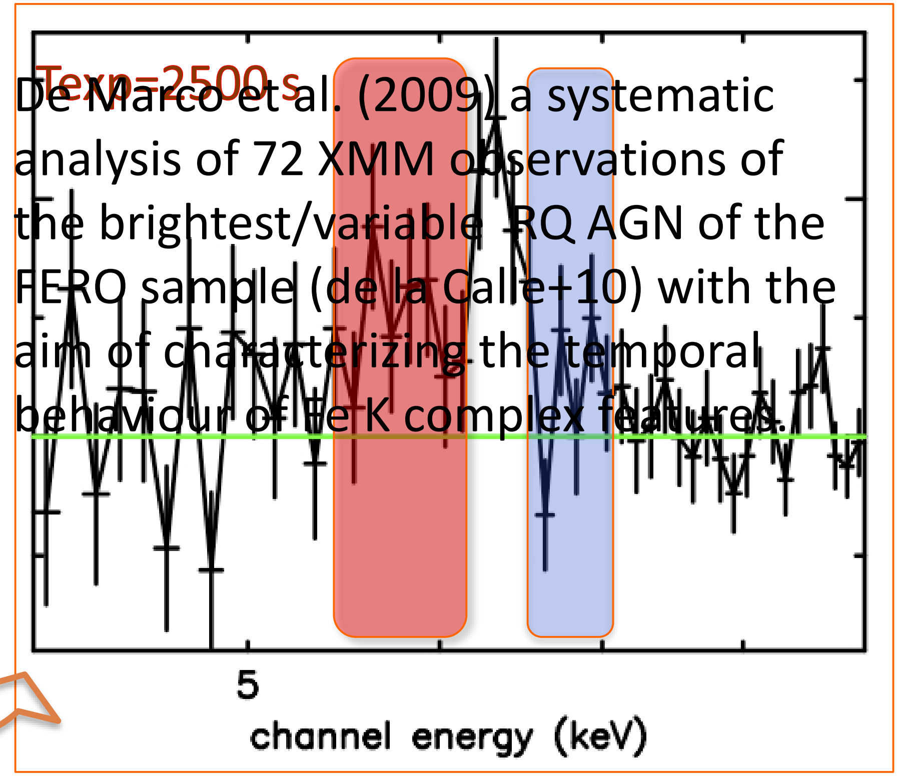
$M_{X\text{-}ray}$=1-5 10^7 M_{sun} – M_{opt}=1.68(0.33)10^7 M_{sun}



The excess emission map on the time-energy plane. The pixel size is 2 ks in time and 100 eV in energy. 4 cycles 25 ks orbital period at 9Rg (Iwasawa+04, Turner+06)

Orbiting spot with XMM-Newton





De Marco et al. (2009) a systematic analysis of 72 XMM observations of the brightest/variable RQ AGN of the FERO sample (de la Calle+10) with the aim of characterizing the temporal behaviour of Fe K complex features.

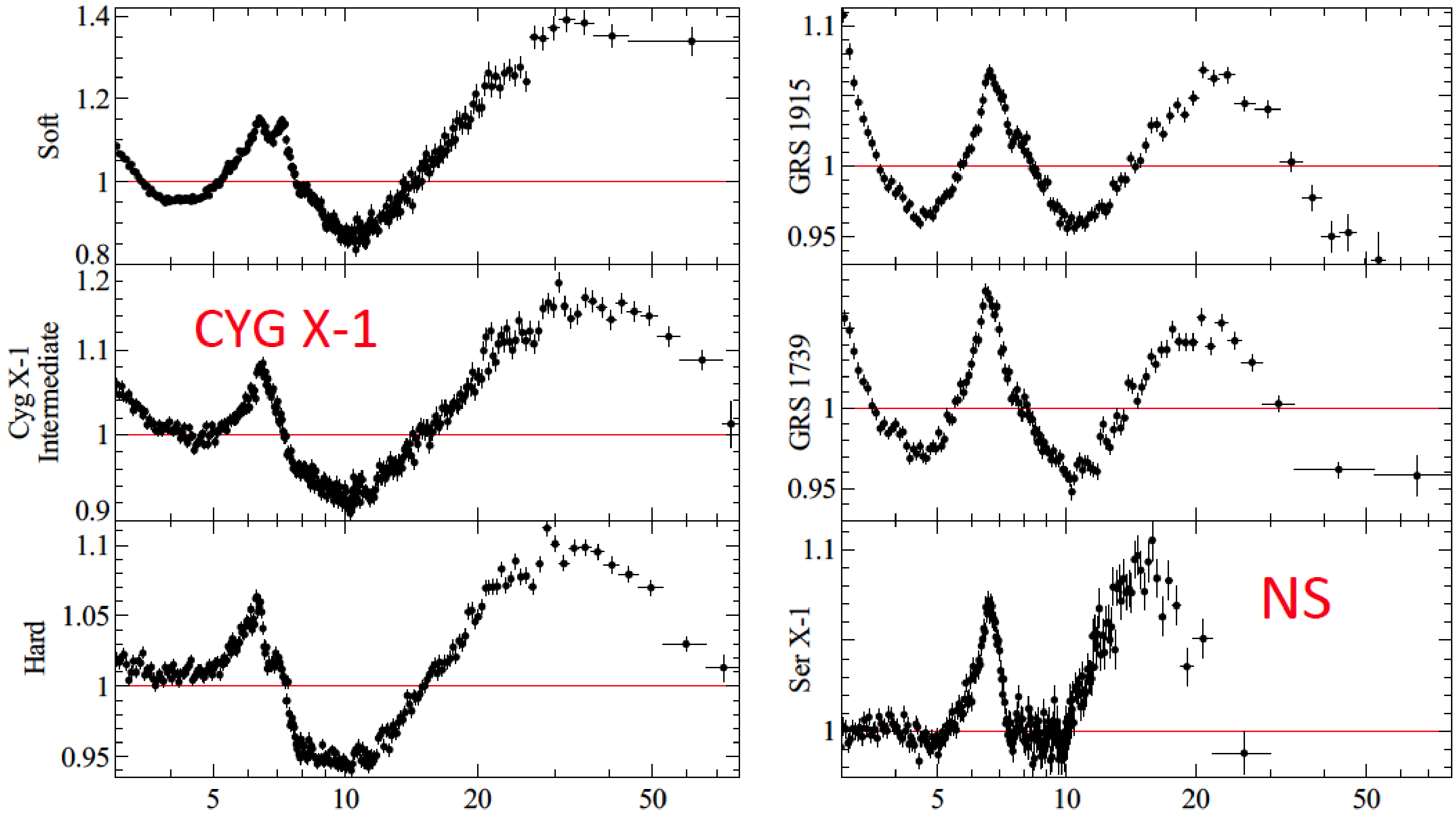
Fe line variability in the red and blue energy bands (5.4-6.1/6.8-7.2 keV) has been found in 12 out 36 observations but still to be confirmed at high cl

Spin in BHB

I. Relativistic reflection (like SMBHs)

II. Continuum fitting: Fitting the thermal 1-10 keV spectrum of the accretion disk

Relativistic reflection with NuStar

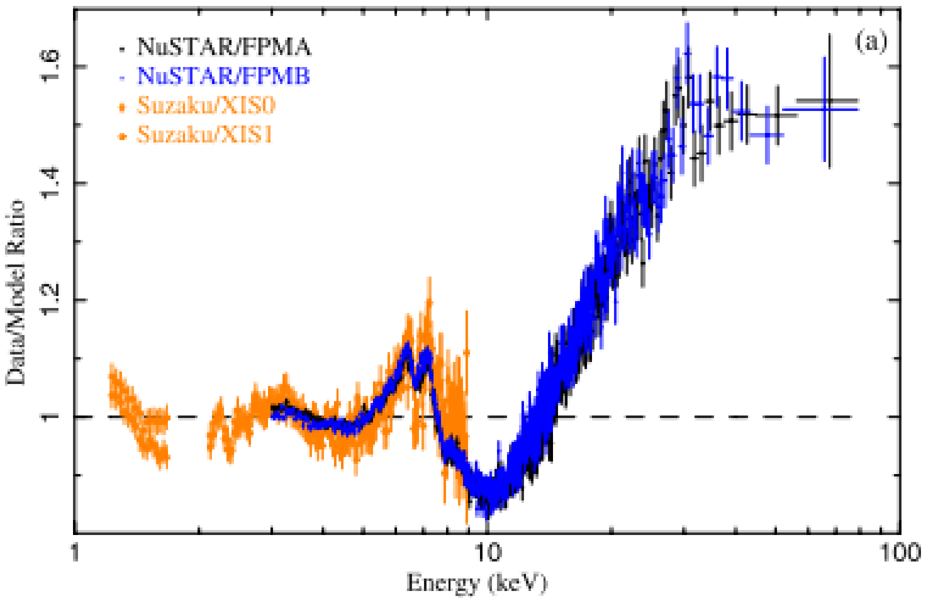


Tomsick+14; Miller+13,15

No Pile-up!

Measuring BH spins in XRB: where do we stand?

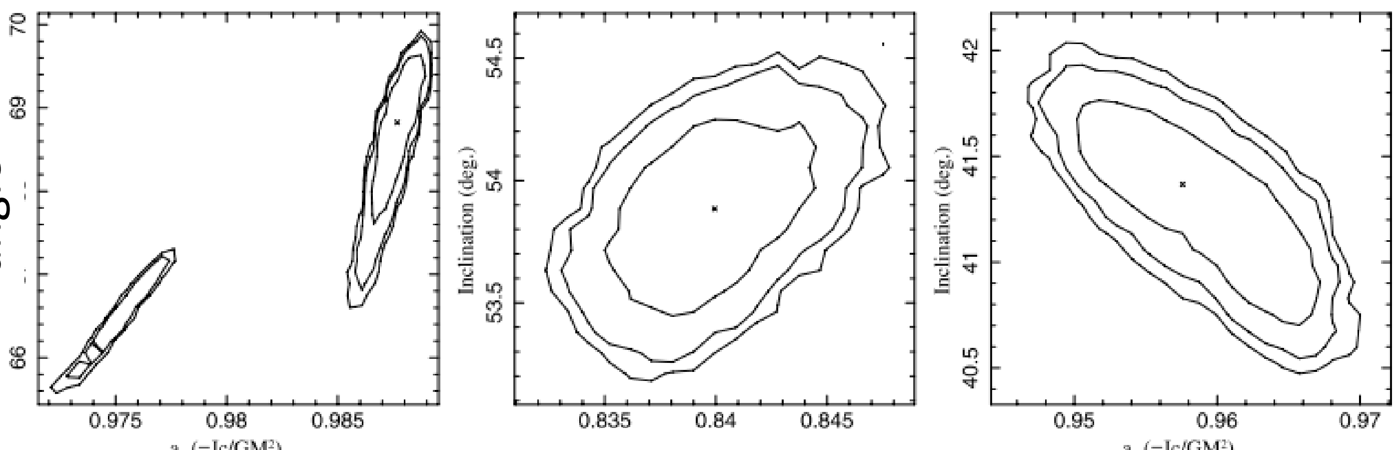
Cyg X-1 high-soft state 30ks



- Huge S/N no pile-up (NuStar)
- Cold/Warm photoionized absorbers
- Relativistic reflection
- Disk inclination disagrees with optical measurements
- Different models for disc emissivity profile produce different value of the BH spin

A big advantage will be to have different simultaneous diagnostics

angle



BH spin

Tomsick+14

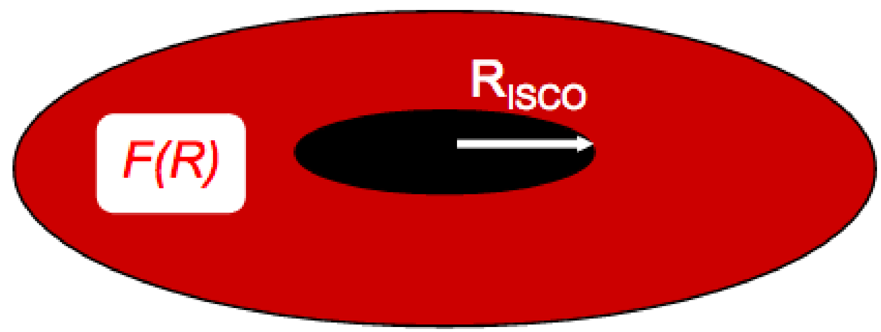
Continuum fitting technique

- Requires accurate values of M, i, D; also knowledge of spectral hardening from disk atmosphere (e.g., Davis+ 2006).

Radius R_{ISCO} of Disk Hole

F and $T \longrightarrow$ solid angle

D and $i \longrightarrow R_{ISCO}$



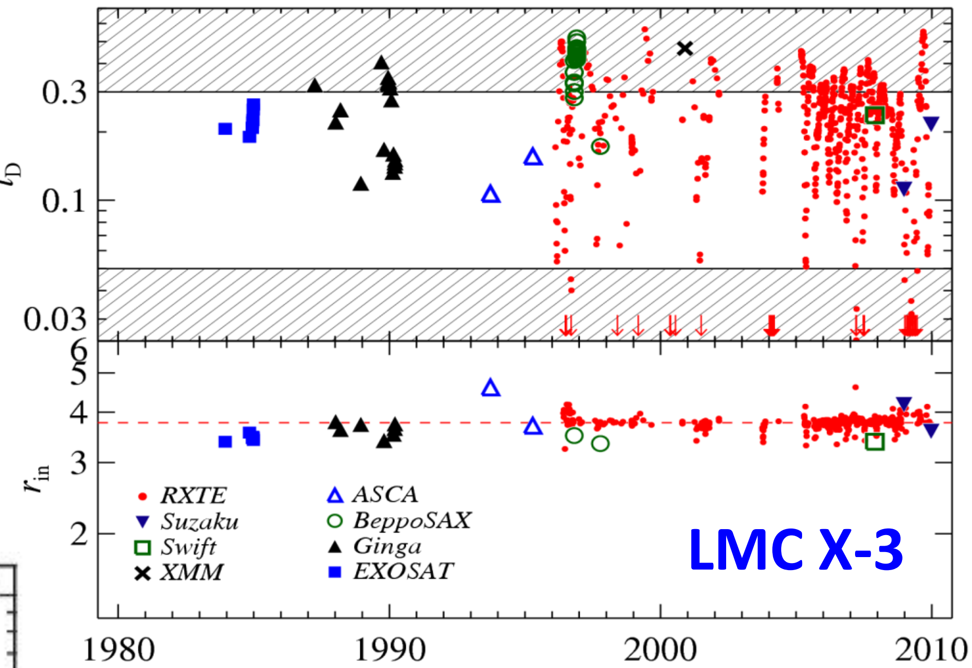
F, T → X-ray observations, assume $T = T_{ISCO}$

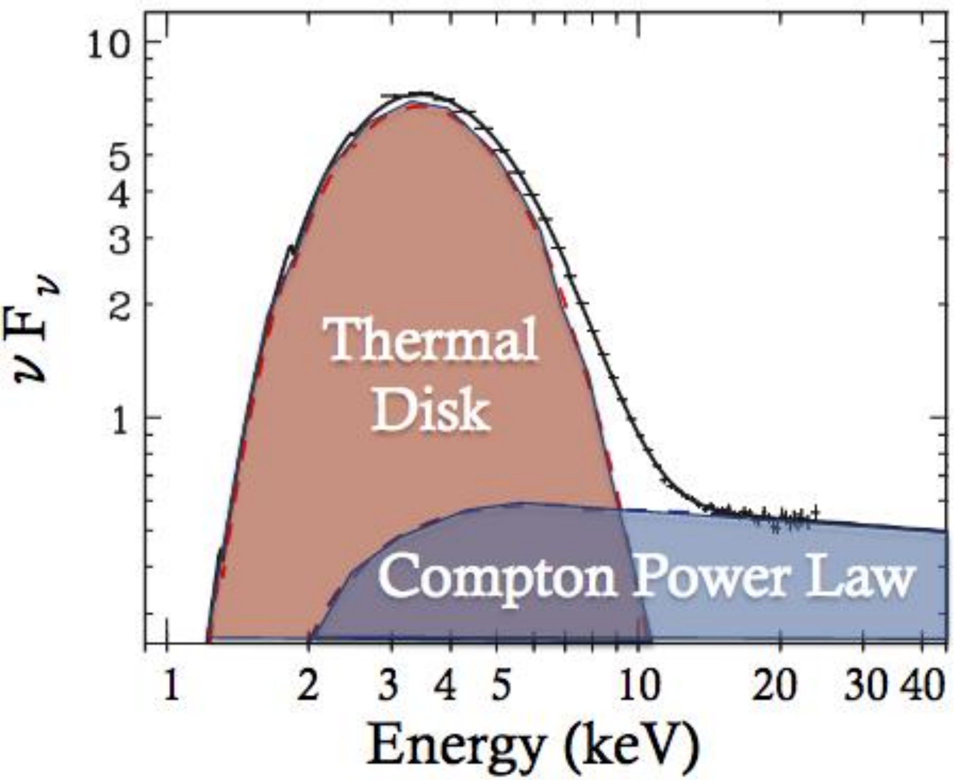
cos (i) and D are known

calculate a from R_{ISCO} and M_{BH}

McClintock+11

CF method and observations





Requirements:

- Spectrumn dominated by Disk components
- Theoretical profile for F(R)
- Thin disk
- Knowledge of i, D, M

Steiner+ 09,+11

BH Spin in XRBs

Black Hole	Spin (CF)	Spin (Fe K)	References
GRS 1915+105	> 0.98	0.98 ± 0.01	McClintock+ (2006); Blum+ (2009)
Cygnus X-1	> 0.97	0.05 ± 0.01	Gou+ (2011); Miller+ (2009)
LMC X-1	0.92 ± 0.06	---	Gou+ (2009)
M33 X-7	0.84 ± 0.05	---	Liu+ (2008, 2010)
4U 1543-47	0.80 ± 0.05	0.3 ± 0.1	Shafee+ (2006); Miller+ (2009)
GRO J1655-40	0.70 ± 0.05	0.98 ± 0.01	Shafee+ (2006); Miller+ (2009)
XTE J1550-564	0.34 ± 0.24	0.76 ± 0.01	Steiner+ (2011); Miller+ (2009)
LMC X-3	< 0.3	---	Davis+ (2006)
A 0620-00	0.12 ± 0.18	---	Gou+ (2009)
GX 339-4	---	0.94 ± 0.02	Reis+ (2009)
XTE J1650-500	0.87 ± 0.01*	0.79 ± 0.01	Miller+ (2009); Miller+ (2009)
SAX J1711.6-380	0.6 ± 0.4*	0.6 ± 0.3	Miller+ (2009); Miller+ (2009)
XTE J1752-223	---	0.55 ± 0.11	Reis+ (2010)
XTE J1908+094	0.75 ± 0.09*	0.75 ± 0.09	Miller+ (2009); Miller+ (2009)
SWIFT J1753.5-0127	---	0.76 ± 0.15	Reis+ (2009)
XTE J1652-453	---	0.5 ± 0.1	Hiemstra+ (2009)

Where are we?

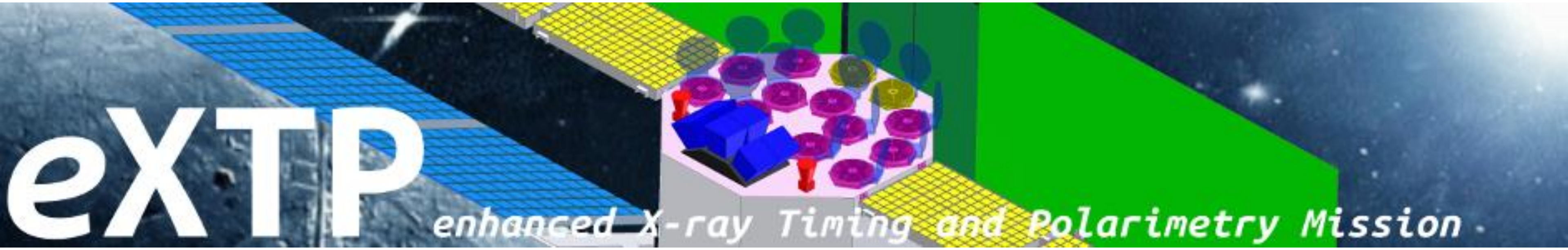
systematic uncertainties related to both the spectral models as well as the calibration of the spectral data (for XRB) dominate statistical errors; there is the danger that one will end up with very precise but inaccurate spin measures

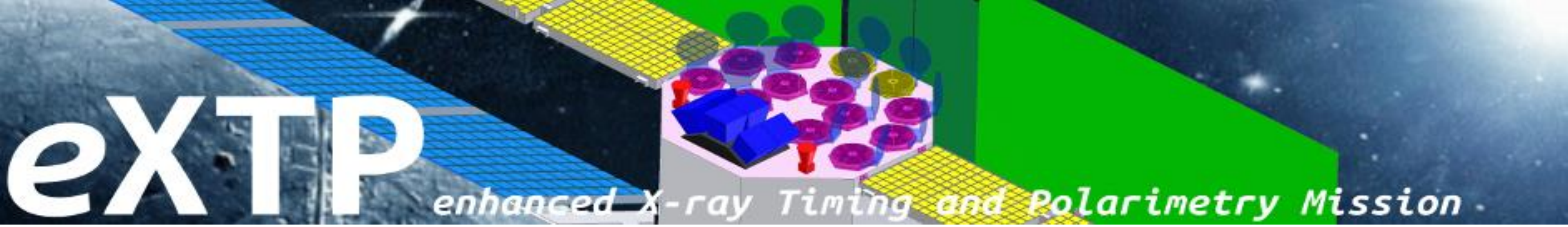
key observations are

1. **Time resolved spectroscopy**
2. Reverberation: time lags (Uttley's talk)
3. Spectral–polarimetry of QPOs (Ingram's talk)

ALL these diagnostics together

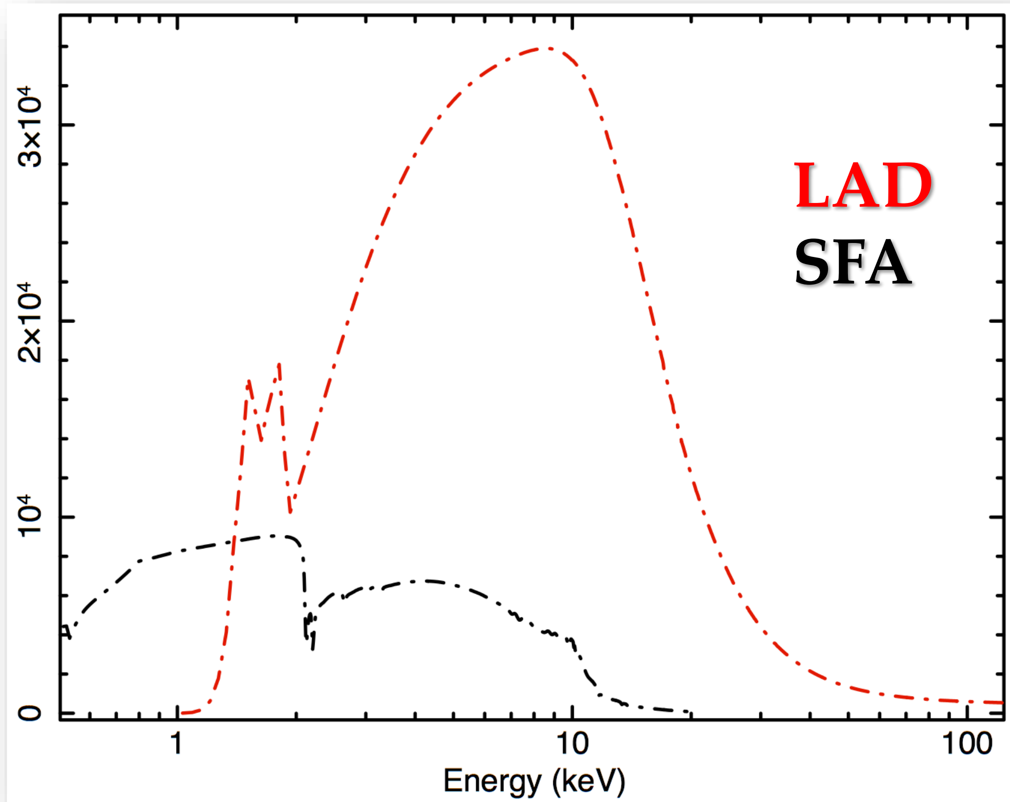
Future perspective with





XTP: SFA

- 9000cm2 @2keV
- 6000cm2 @6keV
- 3700cm2 @10keV
- **Low background**
- **High energy res @6 keV**
- **<2 keV energy band**



LOFT: LAD

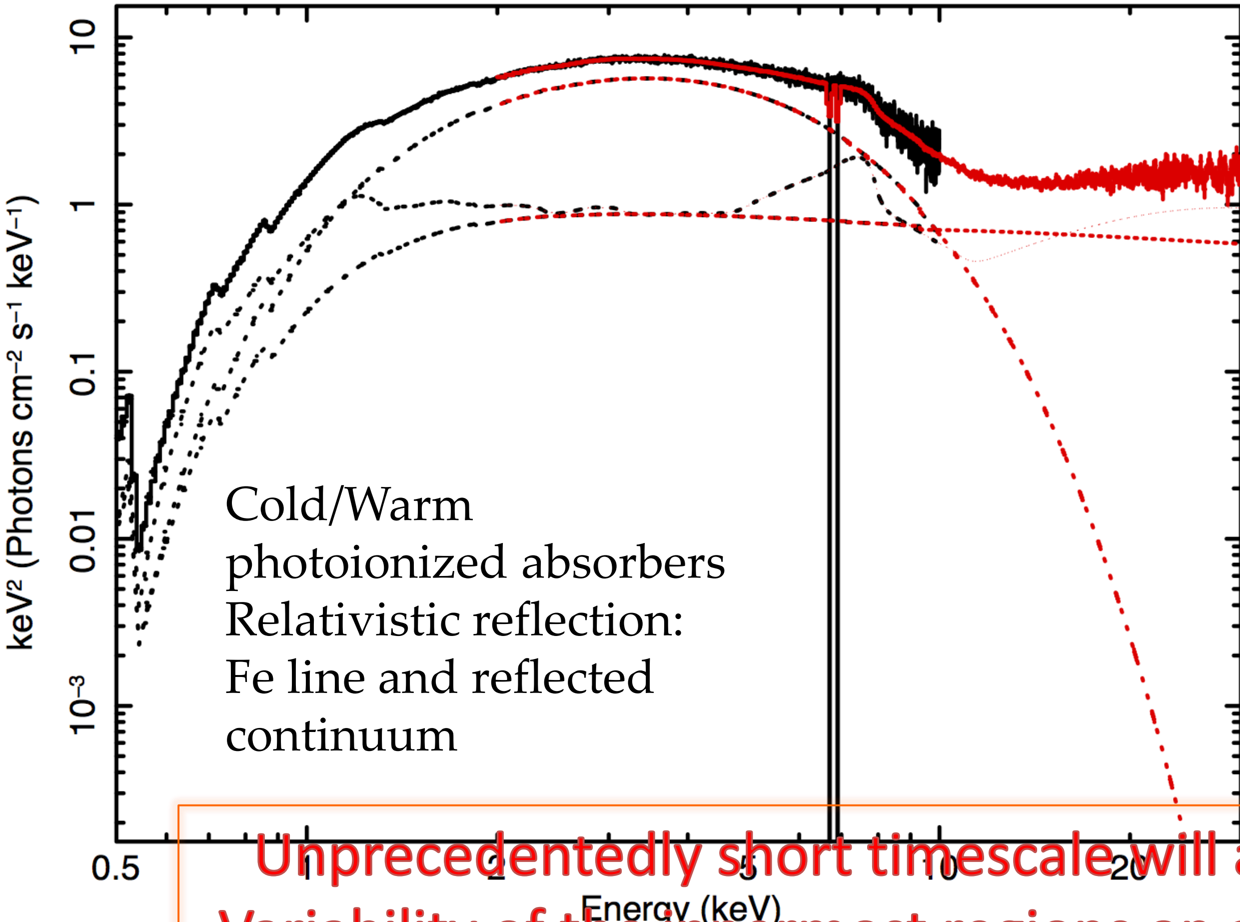
- **3m2 @6 keV/0.1m2 @30 keV**
- Energy res CCD like
- **Broad band 2-30(80) keV**

PFA and WFM

SFG Science Objectives

Science topic	Key performance	Key Instrument
AGN: Doppler tomography	Effective area – BKG – Ene resolution	SFA-LAD
AGN: Fe line	Effective area – BKG – Ene resolution	SFA
XRB: Fe line	Effective area	LAD
X-ray reverberation Disc thermal emission/reverberation	Effective area – soft X coverage	LAD-SFA
QPOs	Effective area	LAD
QPO Phase resolved polarimetry	Effective area	LAD-GPD

eXTP: XRB Fe line



Flux=0.5 Crab

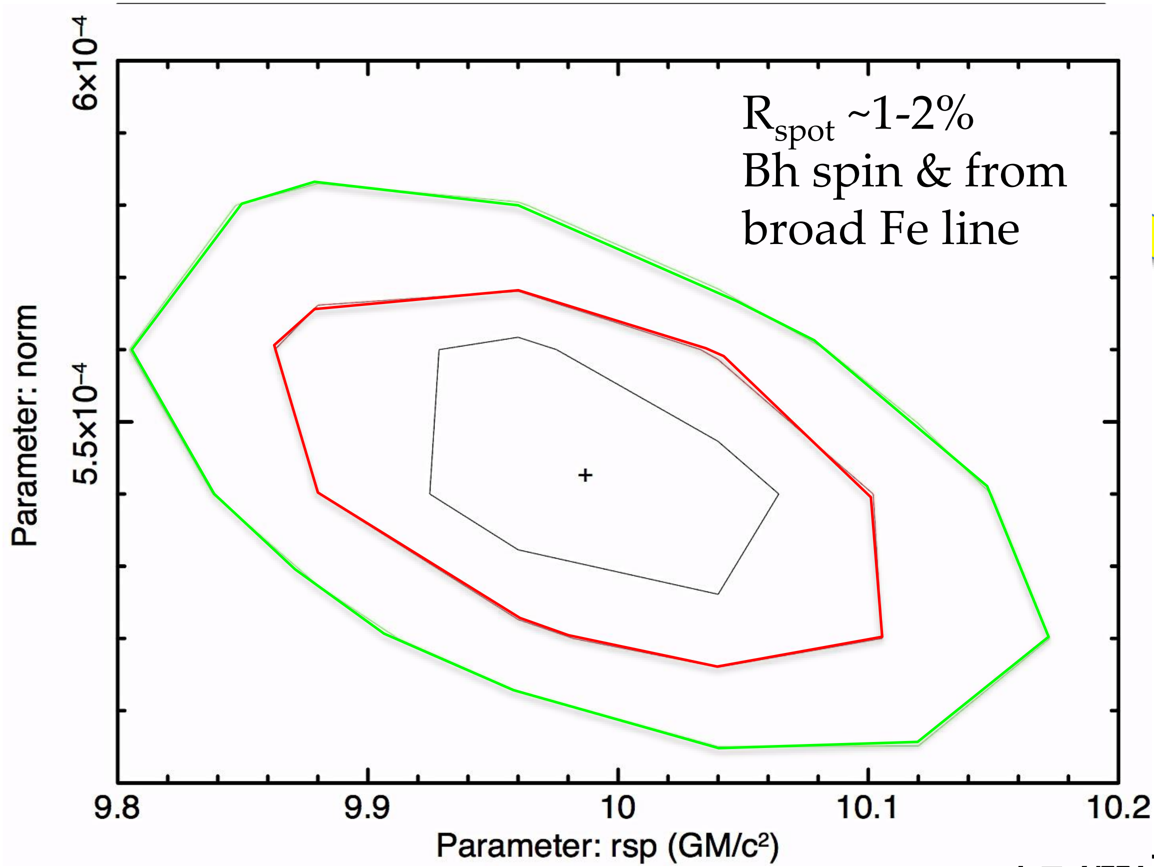
Texp=100 s

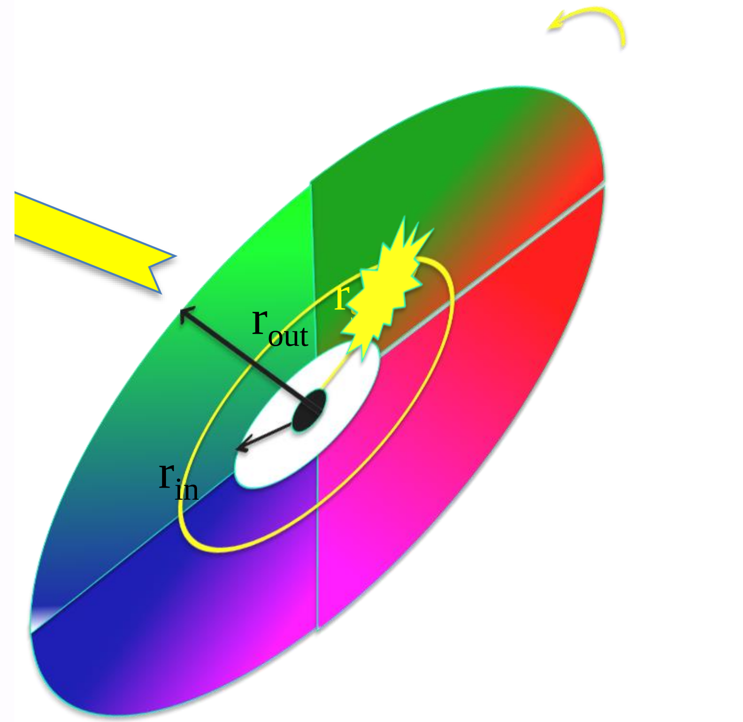
q= disc emissivity index

TP will improve the
I's spin
easurement accuracy
short timescale
100s).

Unprecedentedly short timescale will allow us to investigate Variability of the innermost regions on a timescale comparable with outflows components (e.g disk winds. GRS1915 Nielsen+2011; 4U1630-47Diaz-Trigo+14)

eXTP: AGN Doppler tomography

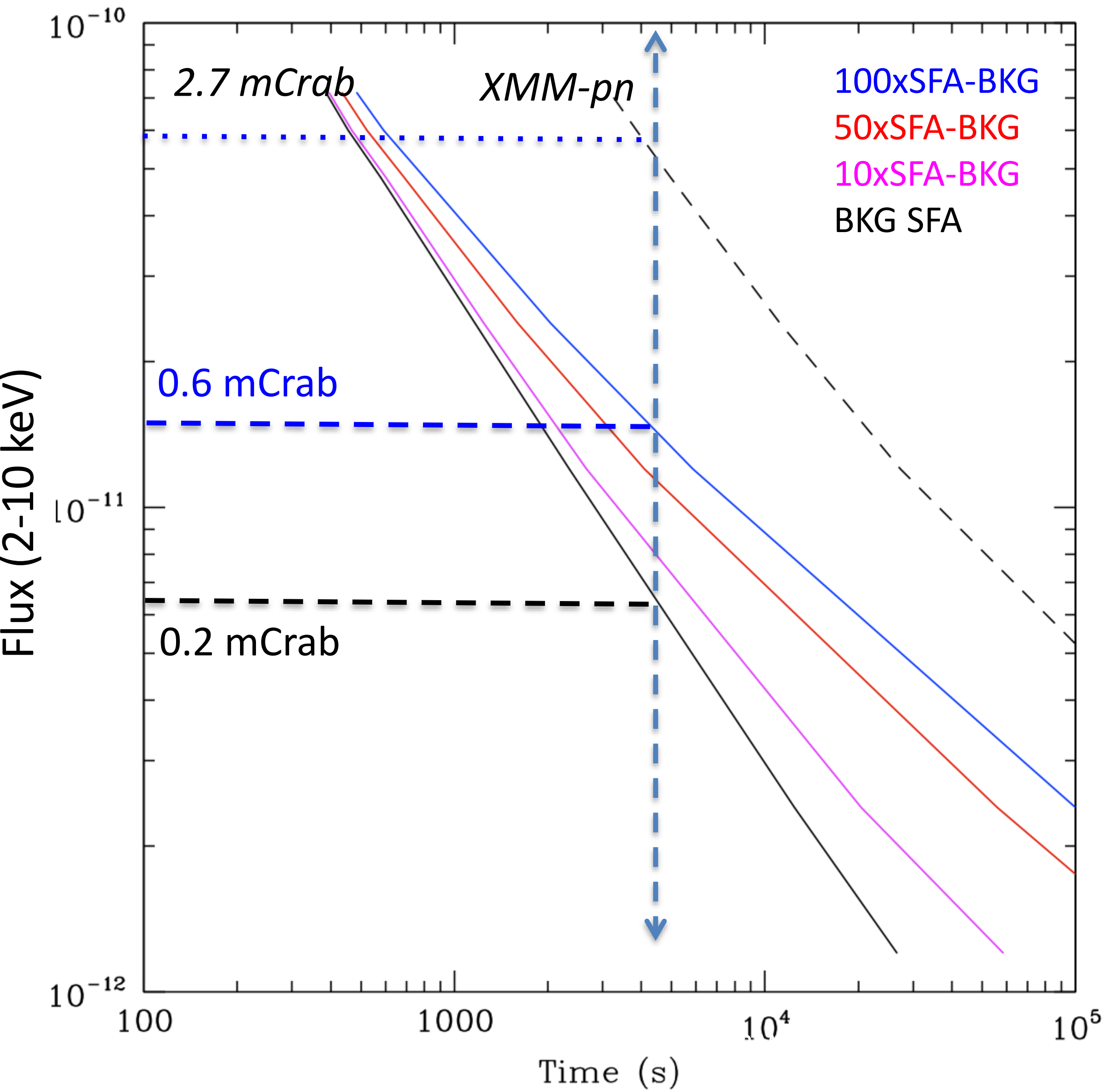




F=3mCrab, EW(average)=30 eV, a=0.5, r_{in}=1r_g, r_{out}=100r_g, θ=30°, ε~r^{-3}, r_{sp}=10r_g, T_{orb}=9 ks

M=3-4 10^6 M_{sun}, a=0.4-0.6, R=0.9(0.1)

Doppler Tomography. Figure of Merit



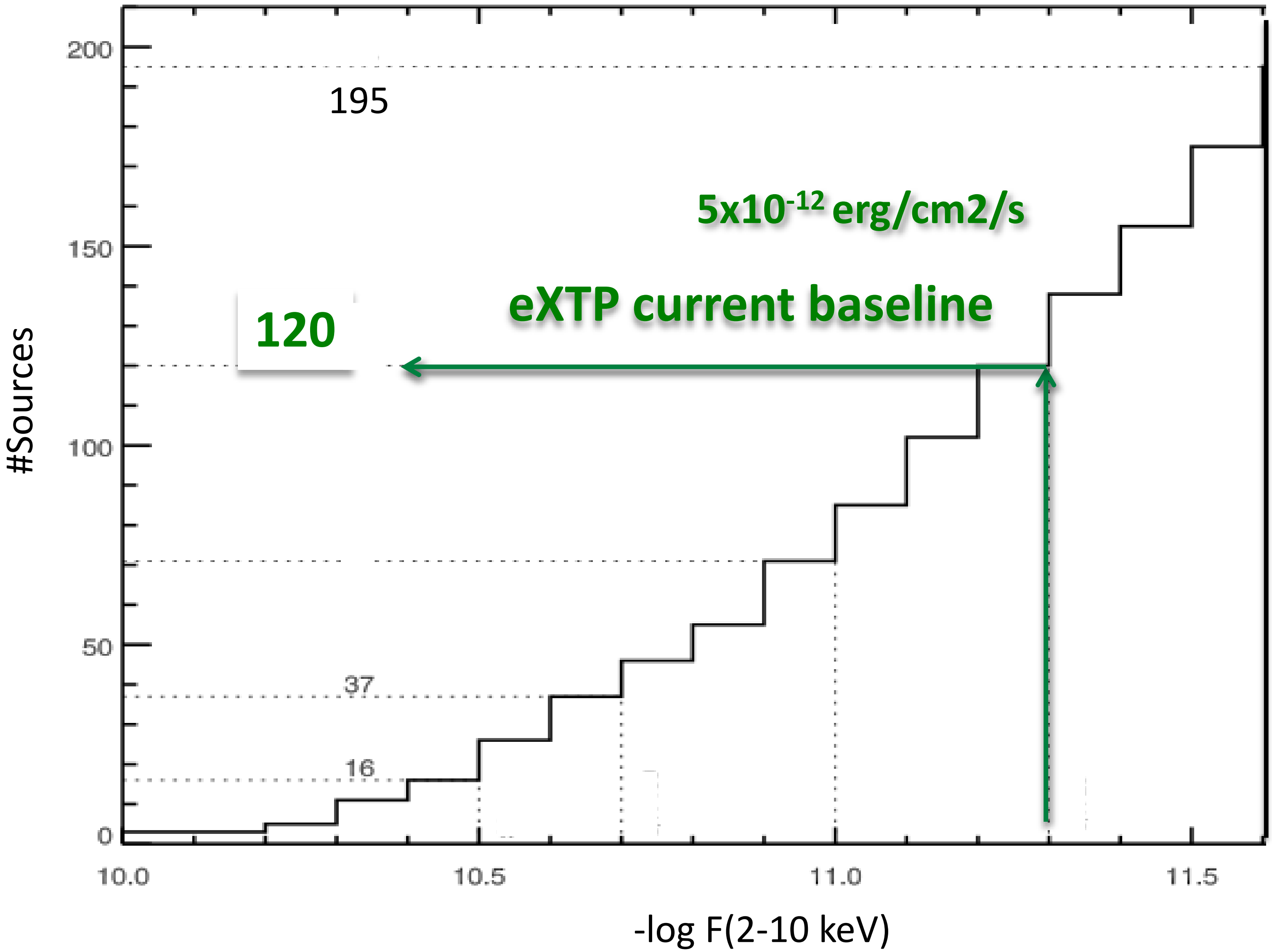
Requirement:

- 3sigma detection
- Line in 5.5-6.5 keV
- σ=100 eV
- EW=50 eV

Time scale

- T_{orb}(ISCO)~5000x(M/10^7 Msun) s – Swartz.
- T_{orb}(ISCO)~500x(M/10^7 Msun) s - Kerr

Doppler tomography with the brightest X-ray AGN

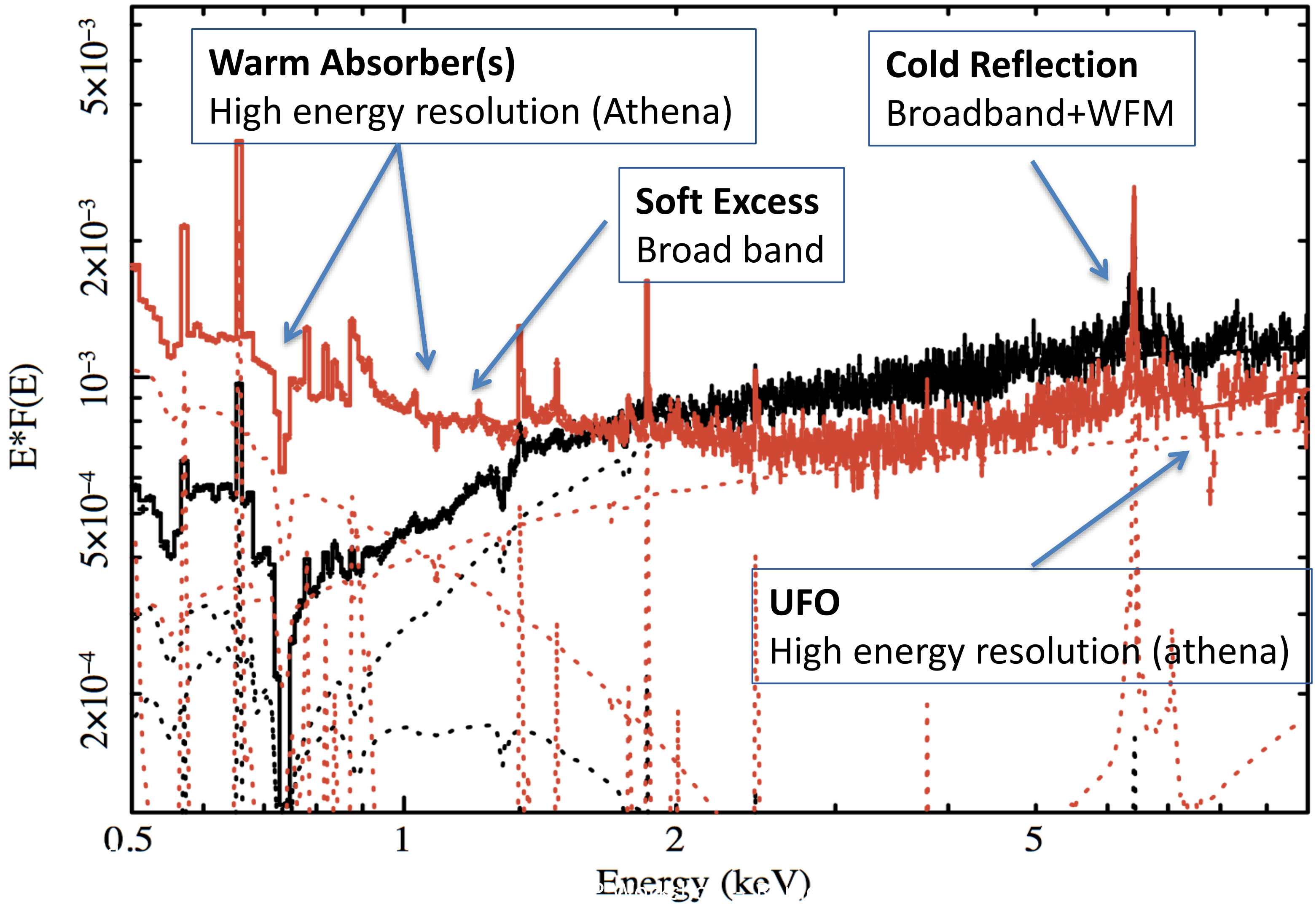


AGN Astrophysics

- ✓ ***Hot Corona*** **is compact, size ~10Rg (reverberation, micorlensing Chartas+09, Fabian+15). Geometry and physics still unknown**
- ✓ ***Soft-excess*** **comptonised warm corona or blurred reflection**
- ✓ ***Cold absorption*** **regions (BLR, Torus), eclipses events, Unified Model for AGN**
- ✓ ***Warm absorption(s)***
- ✓ ***Disk winds and UFOs***

AGN broad band properties

F(2-10 keV)=2e-12 cgs - 100 ks

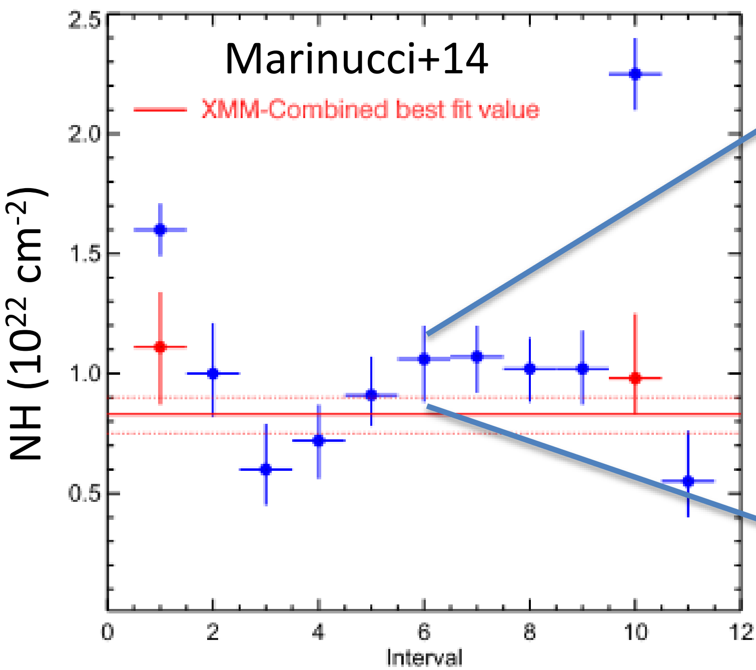


AGN broad band properties

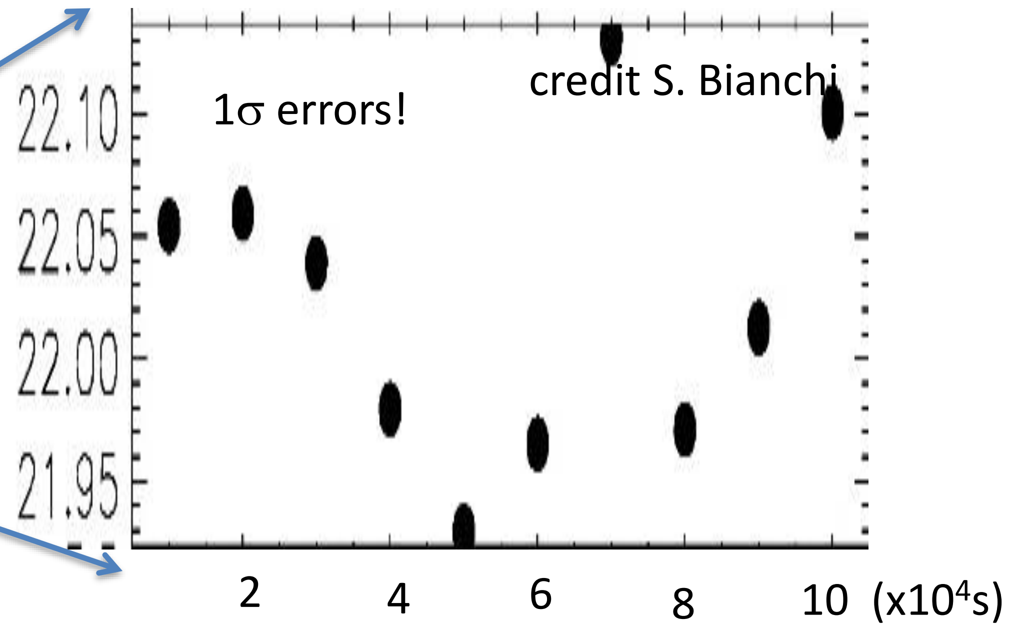
F(2-10 keV)=2e-12 cgs – 10x10 ks

F(2-10 keV)=2e-12 cgs - 10 ks

XMM



eXTP-LFA

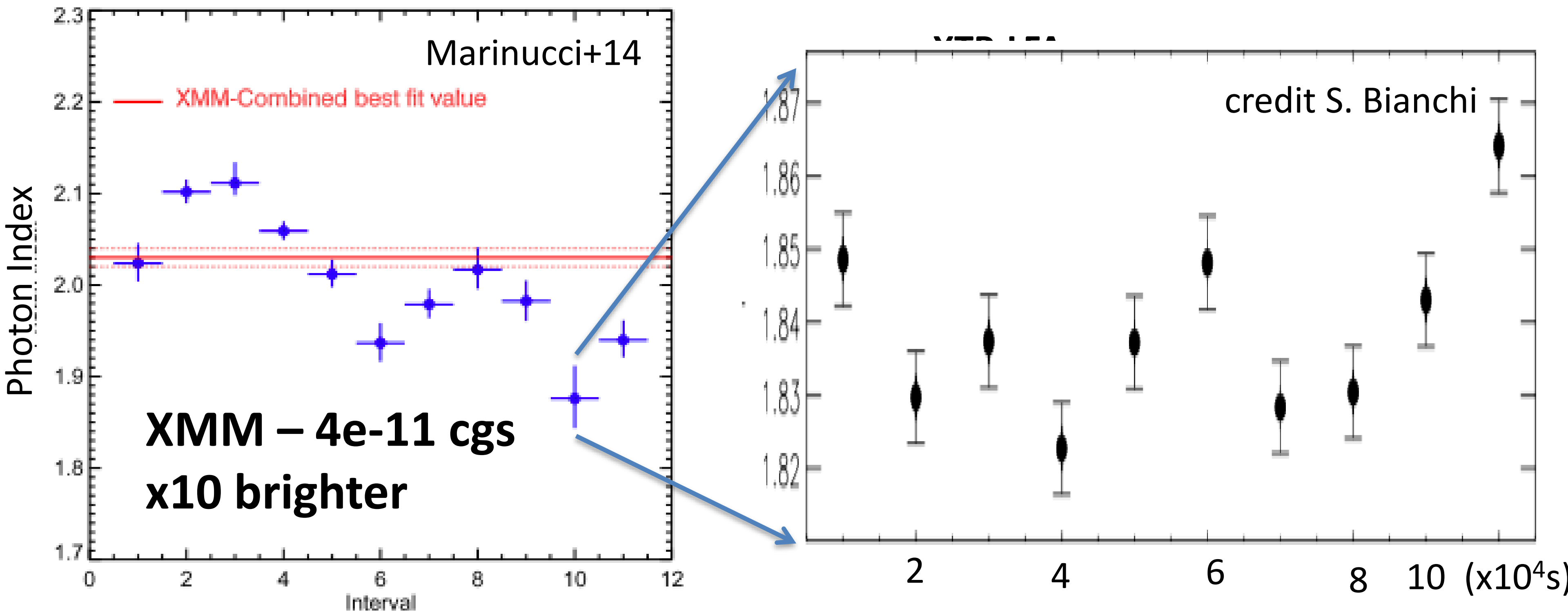


Time resolved spectral variability of the WA components!!

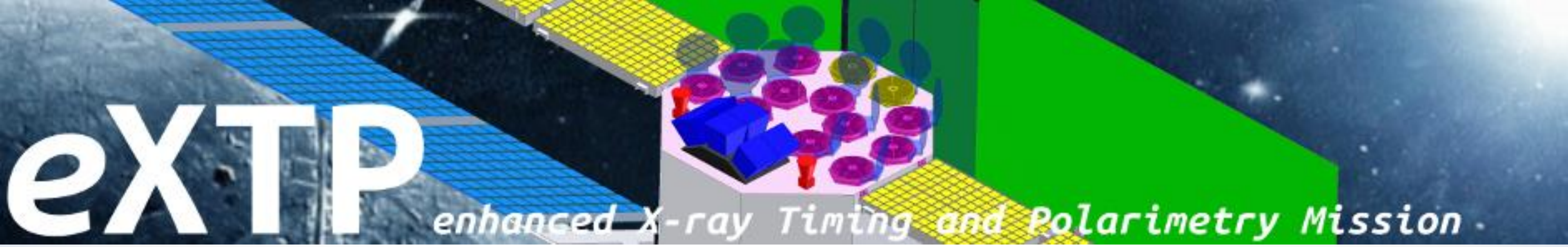
Map from the pc to Kpc scale: disc winds-BLR-torus

AGN broad band properties

F(2-10 keV)=2e-12 cgs – 10x10 ks



Time resolved spectral variability of the primary component



White Paper

Accretion in Strong field gravity regime

Mapping the inner regions around BHs

A. De Rosa, P. Uttley, Lijun Gou, Yuan Liu
and the *eXTP-SFG WG Team*

Submit your application to the SFG-WG
http://www.isdc.unige.ch/extp/swg-registration.html

Summary

- X-ray spectroscopy and timing provide a strong tools for probing accretion under SFG regime. Latest XMM/NuStar results on BHs spin are still not conclusive.
- New key observations are needed to disentangle systematic effects mainly due to modellization (SMBH) or calibration (XRB)
- The eXTP mission is particularly suited to address these issues with 3 different key measurements which complement each other.

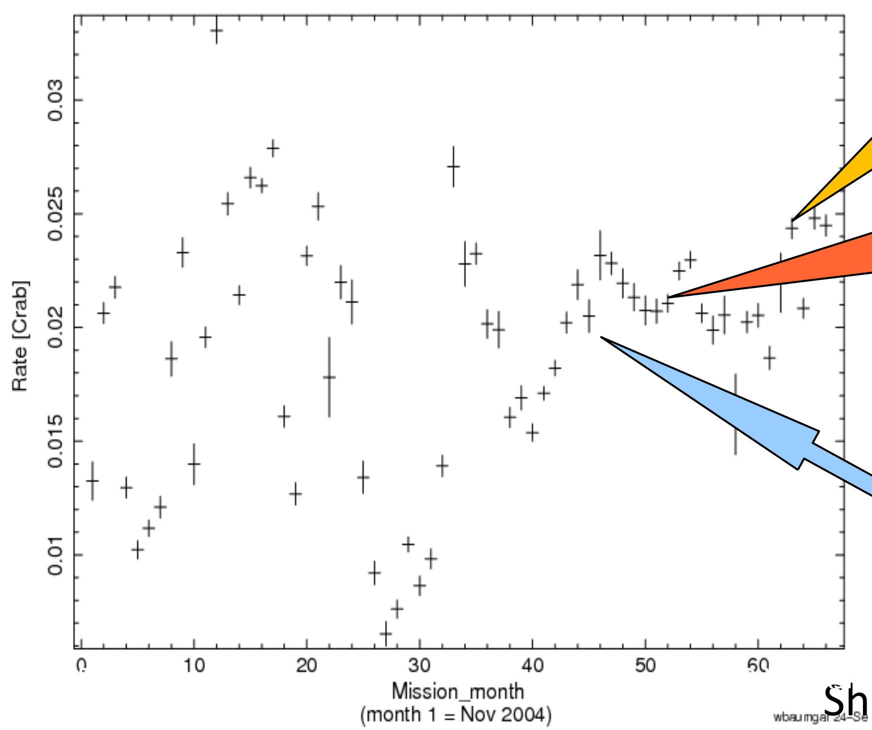
Thank you!

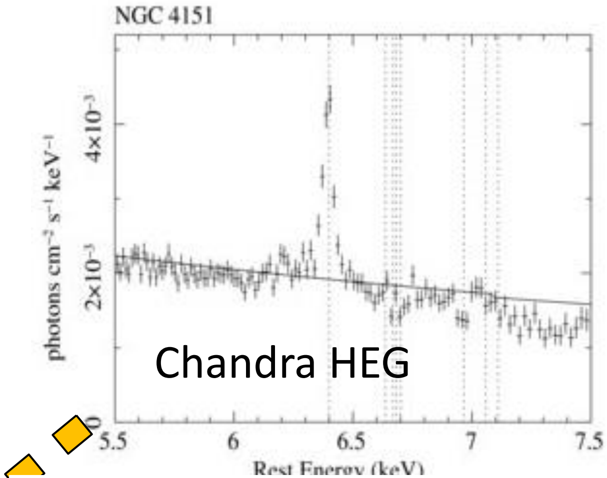
Narrow Fe line Reverberation

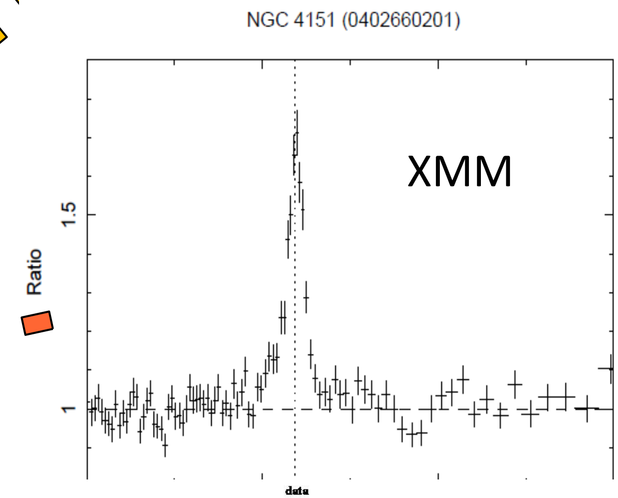
Goal: monitoring the Fe line and the continuum in order to Investigate the geometry and location of the reprocessing material.
Expected time-scales are from weeks to years (BLRs, Torus)

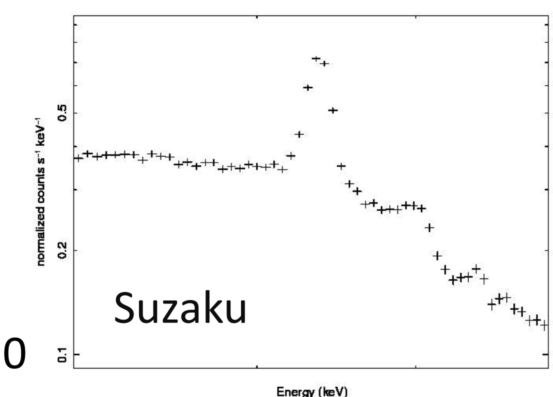
What can be done now?

Swift BAT 'continuous' lightcurves for the continuum
Badly sampled Fe line fluxes from different instruments





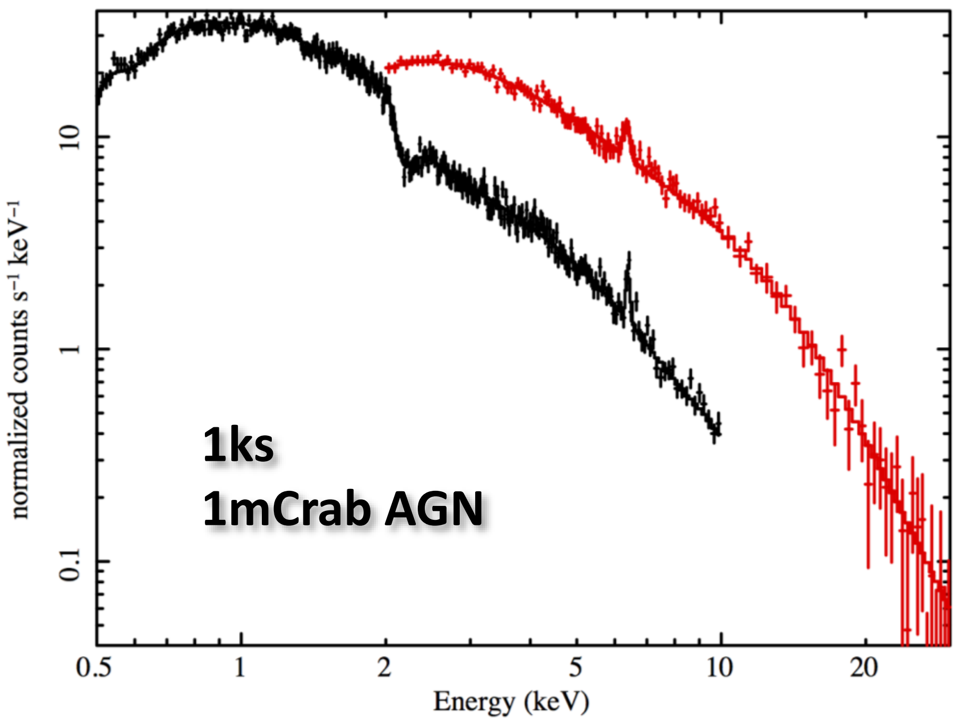




Shu+10, Tombesi+10

Narrow Fe line reverberation with eXTP

- eXTP will perform a well-sampled monitoring for the narrow Fe line (and Compton reflection for the brightest AGN) with short observations
- in 1 ks for 1mCrab AGN the Fe line flux can be recovered with **SFA+LAD** with an uncertainty of ~5-10%
- The **WFM** will produce continuous light-curves with 3σ daily (on average) time-bins for bright sources (10^{-10} cgs in the 7-50 keV band, i.e., above the Fe K edge). Weaker objects (5 $\times 10^{-11}$ cgs) will have 3σ weekly (on average) time-bins
- WFM+SFA+LAD combined capabilities!

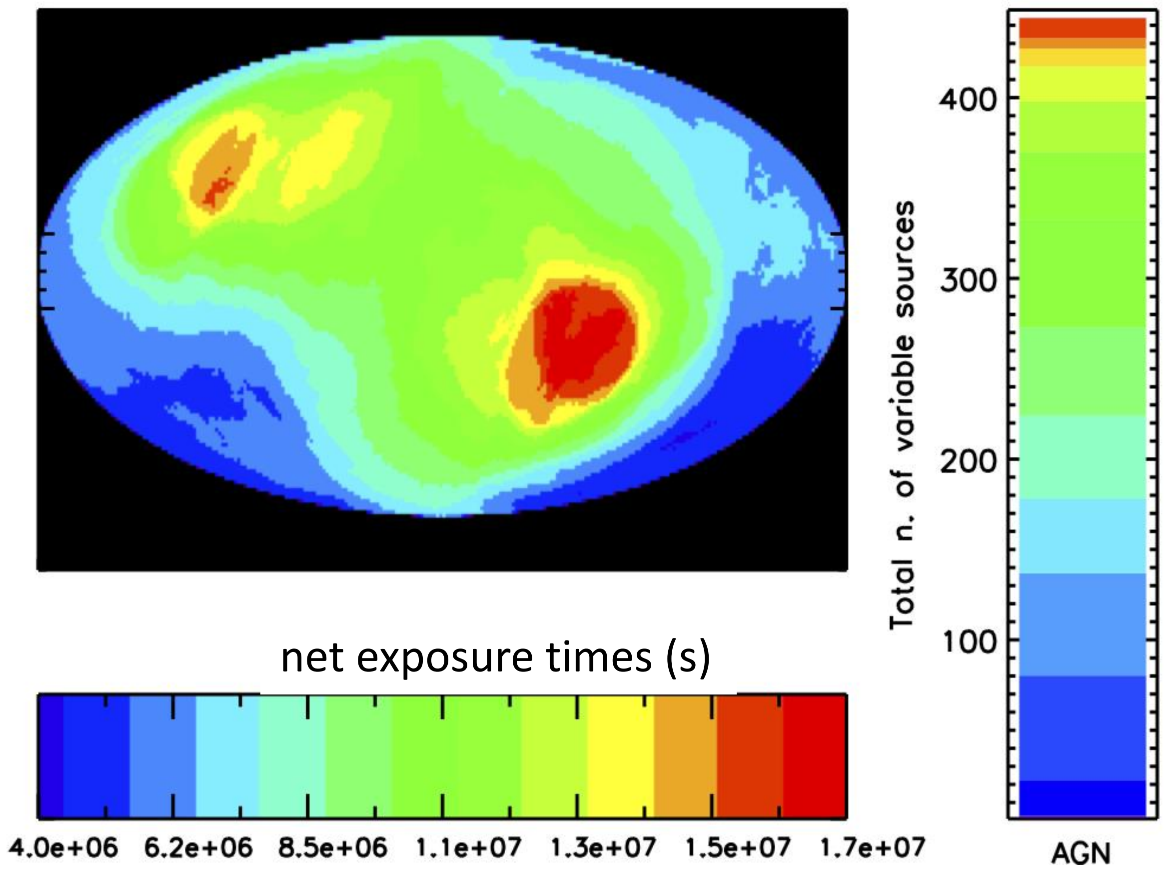


These timescales are perfectly suited for the Fe narrow line reverberation analysis, since the expected timescales are from days to weeks to years (external disk, BLRs, Torus)

AGN variability with the WFM

The vertical colorbar shows the **total number of AGN** for which the WFM will return **light curves with at least 10 points** and where variability will be detected with S/N > 3.

Expected 1 year WFM exposure time



Credit M. Paolillo